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Surveys and Needs Assessment

Factors Associated With Willingness to Plant Non-Bt Maize Refuge and Suggestions for Increasing Refuge Compliance

Dominic D. Reisig

Department of Entomology and Plant Pathology, North Carolina State University, Vernon G. James Research & Extension Center, 207 Research Station Rd., Plymouth, NC 27962 (ddreisig@ncsu.edu)

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Abstract

Southern U.S. growers who plant Bt maize (*Zea mays* L.) must plant a separate non-Bt refuge to maintain Bt susceptibility to pests. North Carolina maize growers were surveyed for intention to plant non-Bt maize refuge, understanding of the importance of refuge, and for their perceptions on actions that would encourage refuge plantings. Identical surveys were conducted and compared before and after a short verbal presentation during 2014 on the logic and necessity of planting refuge. An identical survey was given during 2016, but without a verbal presentation and growers were not asked about actions to encourage planting of refuge. Survey responses from 2014 and 2016 were compared and 2016 survey responses were investigated for possible correlations to environmental factors, such as planted crop area and demographic factors by county. Only 38.3 to 44.3% growers indicated they were planning to plant refuge, and 22 to 29.4% were uncertain about this. Additionally, the verbal county meeting presentation did not increase grower intention to plant more refuge. Although this medium increased understanding directly following the presentation, understanding did not change two years later. Total cropland and farm size were most consistently correlated with intention to plant refuge and understanding of the importance of planting refuge. Future efforts to increase compliance and maintain Bt susceptibility in southern U.S. states like North Carolina should focus on reaching smaller-sized growers. Furthermore, the seed industry could also focus on improved breeding, seed availability, and marketing efforts toward companion non-Bt refuge hybrids, as this was popular with growers.

Key words: blended refuge, block refuge, resistance management, *Helicoverpa zea*

As part of *Bacillus thuringiensis* (Bt) maize (*Zea mays* L.) registrations, the U.S. EPA began to require a structured non-Bt refuge as one tactic of a mandated insect resistance management (IRM) plan to maintain Bt susceptibility in various insect pests during 2000 (U.S. EPA 2001, Bourget et al. 2005). The requirement for a structured non-Bt refuge was one of the lynchpins for the high-dose and refuge strategy to delay resistance. The high-dose and refuge strategy is based on mathematical models showing that fitness is greatly reduced in individuals heterozygous for a single resistance allele as the toxic dose increases above the LD_{99} dose for susceptible individuals (Gould 1998). At the inception of this requirement, a 50% refuge was required for growers in cotton (*Gossypium hirsutum* L.)-growing areas (subsuming the southern United States), while a 20% refuge requirement was implemented for the Corn-Belt (located in the midwestern United States). The difference in requirement centered on the importance of the polyphagous *Helicoverpa zea* (Boddie), which can undergo multiple generations in both Bt-expressing maize and cotton in the southern United States (Gore et al. 2003). In addition to the size requirement (percent of non-Bt to Bt maize), growers must also plant refuges within a specific distance of Bt maize so that Bt-susceptible individuals can find and mate with potentially Bt-resistant individuals. These requirements were determined to be "scientifically sound, protective, feasible, sustainable, and practical to growers" and were also designed to maintain Bt susceptibility for the lifetime of the registration. When separate non-Bt refuge became requisite in the United States during 2001, the lifetime of the registration was until 2006 for Bt cotton expressing Cry1Ac and 2008 for Bt maize (some maize products expressing Cry1Ab and one maize product expressing Cry1F; U.S. EPA 2001).

Refuge requirements in both the Corn-Belt and cotton-growing areas have shifted, in part, as other IRM tactics have been used as part of an IRM strategy to maintain Bt susceptibility (i.e., the inclusion of pyramided toxins (Bates et al. 2005)), and, in part, as evidence arose that non-Bt cotton refuge was relatively unimportant for maintaining Bt-susceptible *H. zea* (Head et al. 2010). Current refuge requirements in cotton-growing areas dictate that Bt maize

product registrants (seed industry) require growers to plant 50% non-Bt structured refuge for maize hybrids expressing a single Bt toxin targeted toward Lepidopteran pests or a 20% non-Bt structured refuge for maize hybrids expressing more than one Bt toxin targeted toward lepidopteran pests.

As part of the condition of U.S. registration, Bt registrants participate in a coalition organization, the Agricultural Biotechnology Stewardship Technical Committee (ABSTC), that, among other functions, reports registrant surveys of Bt maize grower refuge compliance yearly to the U.S. EPA. Using these reports from 2003 to 2008, refuge compliance was documented as trending downward (Jaffee 2009). However, during this time period, these reports did not completely document refuge compliance, which is complex. For example, cotton-growing and maize-growing region compliance results were lumped together, compliance was not always reported for both size (percent refuge relative to Bt) and placement (distance the refuge is located from Bt maize), only growers with 81 hectares of maize and above were included in the survey, and it is likely that nonrespondents to the survey had lower compliance rates than respondents (Bourget et al. 2005). The ABSTC compliance report from 2009 broke out results from the cotton-growing region for the first time, and concluded that compliance was lower in the cotton-growing region compared with maize-growing regions (ABSTC 2010). For example, when correct refuge size was considered during 2009, only 40% of growers from the cotton-growing region were in compliance compared with 76–77% of growers in the maize-growing regions. Although this 2009 result was based on a survey of <100 growers in the cotton-growing region, compared with several hundred from the maize-growing regions, this difference among regions has been measured yearly up to the present time (ABSTC 2011, 2012, 2013, 2014, 2015, 2016). Some reasons for the difference were larger refuge size required for maize hybrids expressing a single Bt toxin targeted toward Lepidopteran pests, greater diversity and complexity in farm operations, a different pest spectrum, the smaller importance of maize relative to other crops in the agricultural system, and smaller farm sizes in the cotton-growing region (ABSTC 2010).

Monsanto, the original registrant of Bt maize, has long recognized that smaller-sized maize growers are less compliant than larger-sized growers. For example, a year 2000 survey (of growers that averaged 224 hectares of Bt maize) found that growers who were not compliant with the refuge size requirement tended to be smaller-sized growers (averaging 175 maize hectares; Monsanto 2001). Moreover, growers that were compliant with the refuge distance requirement tended to be averaged-sized growers (averaging 272 maize hectares). This trend has been noted in South Africa, using the metric of farm size, rather than planted maize area per individual. South African maize growers have explicitly questioned the necessity and pointed out the difficulty of planting a refuge in farming systems with relatively small fields (Kruger et al. 2009). Finally, using U.S. Department of Agriculture National Agricultural Statistics Service survey data, it has been demonstrated that growers with <~80 hectares of maize are more likely to be out of refuge compliance than the results reported by ABSTC (Jaffee 2003, USDA NASS 2003). Hence, starting with the 2009 ABSTC compliance survey, growers from the cotton-growing region were required to grow 40 only hectares of maize to participate in the survey, compared with 81 hectares from the maize-growing region.

Compliance deviations can be explained with a variety of explanations. Some common ones given by growers who have been found to be out of compliance with on farm-checks include weather hampering planting of refuge, problems obtaining the desired refuge seed, planting errors, logistical issues, such as farm layout, and a lack of knowledge concerning refuge (ABSTC 2016). However, both large and smaller-sized growers likely realize that Bt susceptibility is a common property resource and regulation of compliance is potentially costly and difficult (Bourget et al. 2005). Assuming this is true, there are many possible explanations why smaller-sized growers might not be as willing to plant refuge: smaller-sized growers might benefit more from the larger growers who are refuge compliant, smaller-sized growers could be less educated concerning the importance or necessity of planting refuge, smaller-sized growers could perceive less risk from noncompliance, smaller-sized growers may experience a greater overall loss potential from planting refuge compared with less risky Bt options, or a myriad of other explanations.

Survey Objectives

One objective of this study was to survey maize growers in a cotton-producing state, North Carolina, for their intention to plant non-Bt maize refuge, their understanding of the importance of non-Bt maize refuge, and for their perceptions on actions that would encourage them to plant non-Bt maize refuge. A second objective of this study was to test the hypothesis that a traditional Extension method, presenting information directly to growers at county meetings, was an effective medium for changing the outcome of planting more non-Bt maize refuge, as well as for increasing grower understanding concerning the importance of planting non-Bt maize refuge. A third objective of this study was to explore the association of environmental factors that might be correlated with both intention to plant non-Bt maize refuge, as well as the understanding of the importance of planting non-Bt maize refuge. As a cotton-producing state, North Carolina maize growers must plant 50% non-Bt structured refuge for maize hybrids expressing a single Bt toxin targeted toward Lepidopteran pests or a 20% non-Bt structured refuge for maize hybrids expressing more than one Bt toxin targeted toward Lepidopteran pests. A non-Bt cotton refuge is not required for growers who plant Bt cotton.

Survey Description, Methods, and Analysis

North Carolina maize growers were surveyed before the 2014 and 2016 planting seasons during county Extension meetings. Surveys were conducted anonymously using TurningPoint Response Cards (ResponseCard RF LCD, Turning Technologies, Youngstown, OH) and software (TurningPoint 5, Turning Technologies). During 2014, maize growers were asked a series of questions concerning non-Bt maize refuge, followed by an 8-min presentation on the logic, importance, and legal requirement for planting a non-Bt maize refuge, followed by the same survey at the close of the presentation. During 2016, maize growers were surveyed concerning non-Bt maize refuge without a presentation on non-Bt maize refuge.

Prior to the survey, maize growers were handed a TurningPoint Response card and verbally instructed how to use the card, as well as the purpose of the survey and the importance of answering truthfully. The card electronically transmitted the growers' responses and mean results were graphically depicted after each question. Each question was verbally given to the growers and electronically projected so that they could read it. During 2014, ~300 growers were surveyed in 12 meetings representing 16 North Carolina counties: Beaufort, Bertie, Craven, Duplin, Edgecombe, Halifax, Hoke, Nash, Northampton, Pamlico, Pasquotank, Robeson, Scotland, Washington, Wayne, and Wilson. During 2016, ~400 growers were surveyed from 16 meetings representing 30 North Carolina counties:

Table 1. Grower responses to questions concerning intentions to plant non-Bt seed and understanding the purpose and necessity of a non-Bt maize refuge

Do you plan to plant refuge corn (non-Bt seed) this upcoming season?						
	2014			Counties in common from 2014 to 2016		
Answer	Percentage before presentation $n = 268$	Percentage after presentation $n = 271$	Wilcoxon signed-rank test	Percentage after 2014 presentation $n = 181$	Percentage 2016 $n = 201$	Wilcoxon signed-rank test
Yes	41.4 ± 5.6	41.7 ± 5.1	$Z < 0.0001$; $P \leq 1.0000$	44.3 ± 6.6	38.3 ± 5.7	$Z = 0.5813$; $P = 0.5611$
Maybe	22.0 ± 4.2	26.9 ± 4.9	$Z = -0.1733$; $P = 0.8624$	29.4 ± 6.1	23.9 ± 2.5	$Z = 0.1466$; $P = 0.8850$
No	36.6 ± 3.3	31.4 ± 2.3	$Z = -1.1268$; $P = 0.2598$	26.2 ± 2.6	37.8 ± 6.0	$Z = -1.2525$; $P = 0.2104$
Do you understand the logic behind planting non-Bt refuge?						
	2014			Counties in common from 2014 to 2016		
Answer	Percentage before presentation $n = 296$	Percentage after presentation $n = 242$	Wilcoxon signed-rank test	Percentage after 2014 presentation $n = 201$	Percentage 2016 $n = 242$	Wilcoxon signed-rank test
Very well	21.6 ± 2.5	31.0 ± 3.4	$Z = -3.3501$; $P = 0.0008$**	34.6 ± 3.9	30.2 ± 3.3	$Z = 0.2889$; $P = 0.7727$
Well	29.1 ± 4.0	32.2 ± 4.0	$Z = -1.2704$; $P = 0.2039$	44.7 ± 4.7	32.2 ± 2.5	$Z = 1.2043$; $P = 0.2285$
Somewhat	33.8 ± 3.9	26.9 ± 3.1	$Z = 2.7436$; $P = 0.0061$**	18.2 ± 4.0	26.4 ± 3.7	$Z = -1.3480$; $P = 0.1777$
Not at all	15.5 ± 2.7	9.9 ± 1.3	$Z = 2.6016$; $P = 0.0093$**	2.5 ± 1.4	11.2 ± 2.0	$Z = -2.1639$; $P = 0.0305$*
Do you think planting 20% of your corn acreage as non-Bt refuge is necessary?						
	2014			Counties in common from 2014 to 2016		
Answer	Percentage before presentation $n = 301$	Percentage after presentation $n = 297$	Wilcoxon signed-rank test	Percentage after 2014 presentation $n = 203$	Percentage 2016 $n = 249$	Wilcoxon signed-rank test
Yes	24.6 ± 2.9	46.8 ± 3.3	$Z = -3.6975$; $P = 0.0002$**	45.3 ± 3.7	38.5 ± 3.7	$Z = 2.6960$; $P = 0.0070$**
Maybe	42.5 ± 2.9	35.7 ± 3.9	$Z = 1.0106$; $P = 0.3122$	43.6 ± 4.4	34.3 ± 2.9	$Z = 0.1455$; $P = 0.8851$
No	32.9 ± 2.7	17.5 ± 2.7	$Z = 3.4686$; $P = 0.0005$**	11.1 ± 3.4	27.3 ± 4.5	$Z = -2.6029$; $P = 0.0092$**

The same growers were surveyed before and after a presentation on non-Bt maize refuge during 2014 and growers from the same counties as those surveyed during 2014 were surveyed during 2016. Wilcoxon signed-rank test results are presented to compare if the same percentage of growers selected the response before the presentation during 2014, compared with after the 2014 presentation, and if the same percentage of growers selected the response after the 2014 presentation, compared with 2016. *n*—number of responses,

*$P < 0.05$,

**$P < 0.001$.

Bertie, Bladen, Columbus, Chatham, Chowan, Craven, Duplin, Edgecombe, Franklin, Gates, Greene, Halifax, Hoke, Johnston, Jones, Lee, Martin, Nash, Northampton, Onslow, Pender, Pasquotank, Person, Pitt, Robeson, Sampson, Scotland, Vance, Wake, and Warren. These counties represent ~40% of the maize grown on an area-basis in North Carolina.

Maize growers during 2014 were asked a series of seven questions (Tables 1 and 2) pertaining to their intention to plant non-Bt maize refuge, their understanding of non-Bt maize refuge, and factors that might influence their future willingness to plant non-Bt maize refuge both before and following the presentation on non-Bt refuge. Maize growers during 2016 were asked a series of three questions (Table 1) pertaining to their intention to plant non-Bt maize refuge and their understanding of non-Bt maize refuge. Because maize growers in the United States use the term corn for maize, the term corn was used in the questionnaires. Participants in the meetings were given access to real-time results as the survey was conducted (Fig. 1; PowerPoint 2011, Microsoft Co., Redmond, WA). Responses were summed for each meeting and converted to percentage, as participant number varied by meeting and question.

To compare whether grower responses changed in the short term, responses from before and after the presentation during 2014 were compared using a Wilcoxon signed-rank test (PROC NPAR1WAY, SAS Institute 2008). To compare whether grower responses changed in the longer term, participant responses were compared from meetings in counties common to 2014 and 2016 using a Wilcoxon signed-rank test. A separate test was performed for each response from each question before and after the presentation, during 2014, and from meetings with counties in common from 2014 to 2016.

To explore possible associations of environmental factors with grower responses, Farm Service Agency (FSA) crop area data for maize, cotton, and soybean (*Glycine max* L.) were averaged for each county from 2007–2016 (USDA FSA 2016). Maize, cotton, and soybean area was investigated because these are known major hosts for *H. zea* in North Carolina, a species of concern for Bt

Table 2. Grower responses to questions concerning perceptions of actions to encourage the planting of non-Bt maize refuge

How helpful would a 10% rebate for purchasing non-Bt refuge seed be to convince you to comply with the non-Bt refuge requirement?			
Answer	Percentage before presentation $n = 298$	Percentage after presentation $n = 295$	Wilcoxon signed-rank test
Extremely helpful	19.4 ± 3.1	21.3 ± 2.9	$Z = -0.4042$; $P = 0.6860$
Helpful	31.3 ± 5.6	44.0 ± 2.9	$Z = -1.8813$; $P = 0.0599$
Somewhat helpful	37.0 ± 5.4	21.2 ± 2.8	$Z = 2.0789$; $P = 0.0376$*
Not helpful at all	12.3 ± 3.0	9.2 ± 2.9	$Z = -0.2610$; $P = 0.7964$
How helpful would on-farm refuge checks performed yearly by seed companies be to convince you to comply with the non-Bt refuge requirement?			
Answer	Percentage before presentation $n = 279$	Percentage after presentation $n = 283$	Wilcoxon signed-rank test
Extremely helpful	13.2 ± 3.0	14.8 ± 3.1	$Z = -0.2610$; $P = 0.7964$
Helpful	33.2 ± 3.6	37.0 ± 5.0	$Z = -0.6645$; $P = 0.5064$
Somewhat helpful	30.5 ± 4.6	24.0 ± 4.0	$Z = 0.9525$; $P = 0.3407$
Not helpful at all	30.0 ± 2.8	24.2 ± 3.7	$Z = -0.0867$; $P = 0.9309$
How helpful would neighboring farms also complying with refuge requirements be to convince you to comply with the non-Bt refuge requirement?			
Answer	Percentage before presentation $n = 279$	Percentage after presentation $n = 283$	Wilcoxon signed-rank test
Extremely helpful	6.0 ± 2.2	6.8 ± 1.8	$Z = -0.6230$; $P = 0.5333$
Helpful	28.0 ± 4.6	37.7 ± 3.7	$Z = -1.7032$; $P = 0.0885$
Somewhat helpful	35.9 ± 3.2	30.8 ± 4.2	$Z = 1.3285$; $P = 0.1840$
Not helpful at all	30.2 ± 4.7	24.8 ± 4.5	$Z = 0.8959$; $P = 0.3703$
How helpful would companion refuge hybrids available with similar yields be to convince you to comply with the non-Bt refuge requirement?			
Answer	Percentage before presentation $n = 279$	Percentage after presentation $n = 283$	Wilcoxon signed-rank test
Extremely helpful	27.8 ± 2.2	29.3 ± 4.5	$Z = -0.2888$; $P = 0.7753$
Helpful	41.5 ± 4.6	45.8 ± 3.5	$Z = -0.9248$; $P = 0.3551$
Somewhat helpful	24.5 ± 3.2	18.4 ± 3.8	$Z = 1.4738$; $P = 0.1405$
Not helpful at all	9.2 ± 4.7	6.5 ± 1.8	$Z = 0.4073$; $P = 0.6838$

The same growers were surveyed before and after a presentation on non-Bt maize refuge during 2014. Wilcoxon signed-rank test results are presented to compare if the same percentage of growers selected the response before the presentation during 2014, compared with after the 2014 presentation. *n*—number of responses,

*$P < 0.05$.

resistance management (Head et al. 2010). Further logic for using these data was that, for any given year, the area of a single crop can vary widely. However, by using the 10-yr average, these fluctuations should be reduced. In addition, county-level census data were collected for the total cropland, number of farms, farm size, grower age, average net cash farm income of operation, principal operator by primary occupation (both farming and other), and county size (USDA NASS 2012); proportion of total land in cultivation and the proportion of growers who farm as a primary occupation were calculated from these statistics. The proportion of land in maize, cotton, and soybean was calculated by dividing the sum of the 10-yr averages for area planted maize, cotton, and soybean (FSA data) by the total cropland during 2012 (USDA NASS data). Each of these environmental factors from each county was compared with the average grower response for each question at the county level using Pearson product-moment correlation (PROC CORR, SAS Institute 2008). Only 2016 grower responses were used for this analysis, as the response number was higher than that from 2014 (response number in 2016 ranged from 359 to 419 individuals, depending on the question asked) and because this would not confound the possible effect of time on responses between 2014 and 2016. In some cases, growers from multiple counties were present for a single meeting. In meetings where this occurred, the numbers for each specific environmental factor were averaged across counties present for each multiple county meeting.

Survey Results—Intention to Plant Non-Bt Maize Refuge

The percentage of maize growers who intended to plant non-Bt maize refuge during the upcoming season ranged from 3.83 to 44.3, with 22 to 29.4% indicating that they might do so, depending on which counties were included (Table 1). Growers were no more or less likely to plant refuge before or after the presentation on refuge during 2014 or from 2014 to 2016. When growers were surveyed during 2016, there was a positive correlation between growers who said they intended to plant refuge and maize area, soybean area, total maize, cotton, and soybean area, and total cropland on a county level (Table 3). Additionally, there was a positive correlation between growers who said they might plant refuge and cotton area, as well as proportion of growers who farm as a primary occupation, on a county level. Finally, there was a negative correlation between growers who said they might plant refuge and soybean area, total maize, cotton, and soybean area, proportion of land in maize, cotton, and soybean, total cropland, number of farms, farm size, and net cash per farm on a county level.

Survey Results—Understanding the Purpose and Necessity of Non-Bt Maize Refuge

A minority of maize growers understood the logic (well or very well) behind planting non-Bt refuge before the 2014 presentation (Table 1). Directly following the 2014 presentation, knowledge concerning this topic was increased and remained nearly static in 2016. As an exception, the percentage of growers who did not understand the logic of non-Bt maize refuge at all increased from 2014 to 2016. There were no associations with environmental factors and growers who responded that they understood the logic behind planting non-Bt refuge very well or somewhat (Table 4). In contrast, maize area, total maize, cotton and soybean area, maize, cotton, and soybean, total cropland, net cash per farm, and proportion of growers who farm as a primary occupation were positively correlated with growers who indicated that they understood the logic behind planting non-Bt refuge well during 2016 on a county level. Moreover, the total maize, cotton and soybean area, proportion of land in maize, cotton, and soybean, farm size, net cash per farm, and proportion of growers who farm as a primary occupation were negatively correlated with growers who indicated that they did not understand the logic behind planting non-Bt refuge at all during 2016 on a county level.

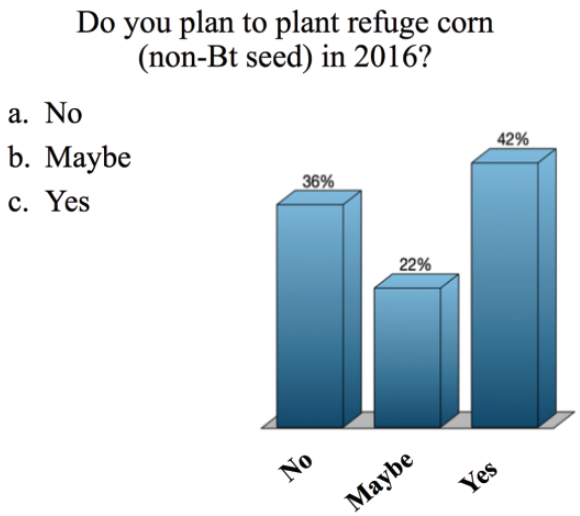

Fig. 1. An example of a survey slide created using TurningPoint software. Results were visible to growers in real time as percentages while they answered anonymously using electronic response clickers.

The percentage of growers who thought that planting non-Bt maize refuge is necessary was 24.6% during 2014 before the presentation and nearly doubled (46.8%) after the 2014 presentation (Table 1). Similarly, the percentage of growers who did not think that non-Bt maize refuge is necessary decreased from 32.9% before the 2014 presentation to 17.5% after the 2014 presentation. In contrast, the opposite trend was observed from 2014 to 2016, with fewer growers indicating that they thought non-Bt maize refuge was necessary during 2016 than during 2014. The percentage of growers who thought that planting non-Bt maize refuge was necessary during 2016 was positively correlated with total cropland, number of farms, farm size, and grower age on a county level (Table 5). There were no associations with these environmental factors and growers who responded "maybe" or "no" to the question of whether planting non-Bt maize was necessary.

Survey Results—Perceptions of Actions to Encourage the Planting of Non-Bt Maize Refuge

Before the 2014 presentation, most maize growers did not think that a 10% rebate for purchasing non-Bt refuge seed would encourage them to comply with the non-Bt refuge requirement, as indicated by the responses in the extremely helpful and helpful category (Table 2). Although the percent of growers across these two response categories did not change significantly, fewer growers indicated that they would find this somewhat helpful after the 2014 presentation than before. The percent of respondents in the "not helpful at all" category remained the same.

Before the 2014 presentation, a minority of maize growers responded that yearly checks of refuge by seed companies and neighboring farm compliance would convince them to comply with non-

Table 3. Growers were asked the question "do you plan to plant refuge corn (non-Bt seed) this upcoming season" in county meetings during 2016, with 359 respondents

Environmental data for Pearson correlation	Pearson correlation values for each response					
	Yes		Maybe		No	
	r	*P*	*r*	*P*	*r*	*P*
Maize hectarage	0.57*	0.026	0.01	0.961	−0.48	0.072
Cotton area	0.25	0.355	0.57*	0.022	−0.55*	0.033
Soybean area	0.54*	0.029	0.35	0.188	−0.70*	0.004
Total maize, cotton, soybean area	0.58*	0.019	0.37	0.163	−0.80**	<0.001
Total cropland	0.54*	0.038	0.33	0.233	−0.65*	0.009
Proportion of land in maize, cotton, soybean	0.17	0.168	0.08	0.008	−0.60*	0.019
Number of farms	−0.02	0.953	0.14	0.600	0.23	0.404
Farm size	−0.01	0.967	0.15	0.585	−0.77**	<0.001
Grower age	−0.02	0.951	0.14	0.613	0.25	0.377
Net cash per farm	0.33	0.236	0.50	0.057	−0.58*	0.025
Proportion of growers who farm as a primary occupation	0.23	0.415	0.53*	0.044	−0.51	0.051
County size	0.04	0.886	−0.21	0.435	0.07	0.804

Percent responses in each category of yes, maybe, and no from each county meeting were analyzed using separate Pearson product-moment correlations to various environmental factors at the county level, captured with USDA FSA and USDA NASS survey data. Table presents correlation values for each analysis.

*$P < 0.05$,

**$P < 0.001$.

Table 4. Growers were asked the question "do you understand the logic behind planting non-Bt refuge" in county meetings during 2016, with 408 respondents

Environmental data for Pearson correlation	Pearson correlation values for each response							
	Very well		Well		Somewhat		Not at all	
	r	*P*	*r*	*P*	*r*	*P*	*r*	*P*
Maize area	0.19	0.472	0.53*	0.035	0.19	0.472	0.53*	0.035
Cotton area	0.22	0.410	0.38	0.146	0.22	0.410	0.38	0.146
Soybean area	0.29	0.270	0.46	0.076	0.29	0.270	0.46	0.076
Total maize, cotton, soybean area	0.28	0.300	0.58*	0.017	0.28	0.300	0.58*	0.017
Total cropland	0.22	0.419	0.53*	0.038	0.22	0.419	0.53*	0.038
Proportion of land in maize, cotton, soybean	0.05	0.840	0.52*	0.040	0.05	0.840	0.52*	0.040
Number of farms	0.15	0.572	−0.05	0.844	0.15	0.572	−0.05	0.844
Farm size	0.15	0.568	−0.05	0.857	0.15	0.568	−0.05	0.857
Grower age	0.14	0.593	−0.06	0.822	0.14	0.593	−0.06	0.822
Net cash per farm	0.42	0.102	0.64*	0.007	0.42	0.102	0.64*	0.007
Proportion of growers who farm as a primary occupation	0.08	0.778	0.55*	0.027	0.08	0.778	0.55*	0.027
County size	−0.10	0.700	0.08	0.768	−0.10	0.700	0.08	0.768

Percent responses in each category of yes, maybe, and no from each county meeting were analyzed using separate Pearson product-moment correlations to various environmental factors at the county level, captured with USDA FSA and USDA NASS survey data. Table presents correlation values for each analysis.

*$P < 0.05$.

Table 5. Growers were asked the question "do you think planting 20% of your maize acreage as non-Bt refuge is necessary" in county meetings during 2016, with 419 respondents

Environmental data for Pearson correlation	Pearson correlation values for each response					
	Yes		Maybe		No	
	r	*P*	*r*	*P*	*r*	*P*
Maize area	0.18	0.522	0.03	0.921	−0.16	0.562
Cotton area	0.48	0.059	−0.17	0.530	−0.25	0.376
Soybean area	0.09	0.734	0.17	0.526	−0.31	0.262
Total maize, cotton, soybean area	0.09	0.743	0.16	0.548	−0.34	0.215
Total cropland	0.55*	0.034	0.07	0.805	−0.48	0.069
Proportion of land in maize, cotton, soybean	−0.10	0.732	−0.06	0.824	0.14	0.631
Number of farms	0.58*	0.018	−0.38	0.147	−0.22	0.424
Farm size	0.58*	0.017	−0.38	0.147	−0.10	0.711
Grower age	0.58*	0.018	−0.38	0.151	−0.18	0.530
Net cash per farm	−0.13	0.650	0.48	0.070	−0.38	0.162
Proportion of growers who farm as a primary occupation	0.20	0.469	0.02	0.944	−0.17	0.540
County size	−0.18	0.500	0.14	0.602	−0.06	0.837

Percent responses in each category of yes, maybe, and no from each county meeting were analyzed using separate Pearson product-moment correlations to various environmental factors at the county level, captured with USDA FSA and USDA NASS survey data. Table presents correlation values for each analysis.

*$P < 0.05$.

Bt refuge requirements, as indicated by the responses in the extremely helpful and helpful category (Table 2). Both of these potential actions remained an unpopular method to boost refuge compliance after the 2014 presentation. Finally, a majority of growers thought that having non-Bt refuge hybrids available with similar yields would convince them to comply with the non-Bt refuge requirement, as indicated by the responses in the extremely helpful and helpful category (Table 2). The percentage of respondents in each category of this question remained unchanged after the 2014 presentation compared with before.

General Survey Implications

Maize growers in North Carolina, a cotton-producing state, were less likely to plant non-Bt maize refuge than previous U.S. surveys, with 38.3 to 44.3% planning to plant refuge, and 22 to 29.4% uncertain about planting refuge. Additionally, the traditional Extension method of dispensing information via in-person county meetings was not an effective medium to increase grower intention of planting of more non-Bt maize refuge. While this medium did increase grower understanding concerning the importance of planting non-Bt maize refuge in the short term (*viz.*, directly after a presentation on refuge), this did not change grower understanding when they were surveyed two years later. Moreover, the factors of total cropland and farm size were most consistently correlated with maize growers' intentions to plant refuge as well as the understanding of the importance of planting non-Bt maize refuge.

A previous study showed that 78 to 86% of United States maize growers complied with the non-Bt maize refuge planting and distance requirement during 2008, but that this percentage had decreased from

92 to 95% during 2005 (Jaffee 2009). Survey responses from my study indicate that non-Bt maize refuge compliance for North Carolina is likely lower, and comparable with results from current ABSTC compliance survey results from the cotton-growing region. For example, 30 to 37% of 2014 growers and 36 to 41% of 2015 growers from the cotton-growing region, and 7 to 11% of 2014 growers and 0% of 2015 growers in the maize-growing regions, indicated that they planted no "maize borer refuge" (presumably meaning *Ostrinia nubilalis* (Hübner) refuge) during 2014 and 2015, respectively (ABSTC 2015, 2016). In my survey 26.2 to 37.8% of growers indicated that they were not planning to plant refuge in the upcoming season. Furthermore, since North Carolina maize growers would have purchased seed for the next planting season by the time they were surveyed, many growers in the uncertain category (those that answered maybe they will plant refuge) probably did not plant non-Bt refuge maize during that planting season. Moreover, the grower survey did not include questions regarding refuge size or configuration requirements. If such questions were included, estimated compliance would have likely been even lower (Goldberger et al. 2005, Andow et al. 2010).

Implications of Non-Bt Refuge in the Southern United States

Blended refuge, where non-Bt seeds are planted directly adjacent to Bt seeds within the same row, is permissible for some Bt maize toxins in the Midwest, which are primarily focused on controlling the main pests of maize in this region, root-feeding *Diabrotica spp*., and, to a lesser degree, lepidopteran pests, such as *Diatraea grandiosella* (Dyar) and *O. nubilalis* (Onstad et al. 2011). In contrast, ear-feeding lepidopteran pests are more problematic in the southern United States, some of which overlap in Midwest areas where blended refuge is permitted, such as *H. zea*, *O. nubilalis*, and *Spodoptera frugiperda* (J.E. Smith). Ear-feeding insects present a major challenge for resistance management in a blended refuge scenario, as non-Bt and Bt plants can cross-pollinate and dilute the effectiveness of Bt, by creating kernels with differential toxin expression (Chilcutt and Tabashnik 2004, Burkness and Hutchison 2012, Yang et al. 2014). *Helicoverpa zea* completes most of its life cycle within the ear. Therefore, larvae of this insect can survive better on non-Bt and Bt cross-pollinated ears compared with Bt kernels pollinated by pollen from a Bt plant (Burkness et al. 2011, Yang et al. 2014). Hence, structured non-Bt maize refuge should delay the development of resistance more than blended refuge for *H. zea* (Caprio et al. 2015). This pest is a major focus for Bt resistance management in the southern United States not only because it is an ear-feeder in maize, but because it will also use cotton as a host. Although southern U.S. lepidopteran pests other than *H. zea* will feed on both non-Bt maize and cotton (e.g., *O. nubilalis*, *Spodoptera exigua* (J.E. Smith), and *Spodoptera frugiperda* (J.E. Smith)) and are targets of resistance management across both of these crop systems, many of the currently planted Bt maize and cotton hybrids and varieties are very effective to manage these insects (Hutchison et al. 2010, Siebert et al. 2012, Reisig et al. 2015). In contrast, *H. zea* has been demonstrated to feed and reproduce on both Bt maize and Bt cotton. Resistance can occur when the high dose and refuge resistance management strategy is not followed (Huang et al. 2011). Consequently, field resistance could be expected with *H. zea* and Cry1A traits in maize soon, as these toxins do not meet the category of high dose (Storer et al. 2001, Reisig and Reay-Jones 2015), and refuge compliance, as demonstrated by this study, is low. When non-Bt maize structured refuge compliance is 50%, the development of *H. zea* resistance has been modeled as equal to, or faster than, the development of resistance when blended refuge is planted (Pan et al. 2015). Furthermore, this modeling study determined that maize pyramided with a Bt toxin highly effective and high-dose for *H. zea*, Vip3A (Yang et al. 2015), could delay resistance longer than maize without this toxin. Consequently, resistance to this insect in North Carolina could be delayed through the introduction of this toxin in maize. Since field injury has been documented from *H. zea* in the pyramided maize hybrid containing the toxins Cry1F x Cry1Ab x Vip3Aa20 (Reay-Jones et al. 2016), there is at least some indication that Vip3A may not be as much of a high-dose toxin as previously thought. Therefore, it is critical that the introduction of widespread plantings of blended non-Bt maize refuge, or an increase in non-Bt maize refuge compliance, be achieved to maintain susceptibility of *H. zea* to Vip3A.

Implications for Non-Bt Refuge Outside the United States

Non-Bt refuge planting varies where Bt crops are grown. Similarities can be drawn between Brazil and the United States, as multiple species of Bt crops are grown that can mechanistically filter species for resistance across crops. Both Bt maize and Bt cotton are grown in common between Brazil and the United States. Furthermore, although non-Bt maize refuges are recommended in Brazil, they are not mandatory, with some report that they not being planted as recommended (Monnerat et al. 2015). Quantitative measurements of non-Bt maize refuge in Brazil could provide an interesting comparison to the United States. For example, based on the results of my survey, I would expect that less non-Bt maize refuge is being planted in the South and Southeastern regions of Brazil that have less maize, cotton, and soybean compared to a region such as the Cerrado, where these crops are intensively cultivated on much of the area.

In contrast to Brazil and the United States, cotton is the only Bt crop grown in Australia and China. Until recently, cotton was the only Bt grown in India, but now Bt *Solanum melongena* (L.) is also grown in this country. Given the pest complex in *S. melongena*, and the relatively small acreage of this crop (Choudhary and Gaur 2009) planted to Bt varieties compared to cotton (Morse et al. 2005), *S. melongena* is unlikely to act as a driver of resistance for Bt cotton. Australia Bt cotton growers are required to plant non-Bt cotton refuge and rely on natural refuge, as well as a cultural control tactic of pupal destruction to delay resistance (Downes et al. 2016). On the contrary, China does not require growers to plant non-Bt refuge, relying on other crops to serve as refuge for the target insect of Bt cotton, *Helicoverpa armigera* (Hübner). Wu et al. (2008) state that the implementation of non-Bt refuge in Chinese cotton would be difficult, as many growers tend relatively small fields (Jin et al. 2015), making education a challenge. The results of my survey support their reticence, as farm size was negatively correlated with willingness to plant non-Bt refuge.

Reassessing the Traditional Extension Method of Oral Presentation for Increasing Knowledge and Changing Practices. How Do Growers Really Make Decisions for Planting Non-Bt Refuge?

My grower survey focused on one tactic to delay resistance—increasing non-Bt maize refuge compliance by using a traditional Extension method of presenting information directly to growers at county meetings. Although knowledge concerning the logic and need to plant refuge was increased in the short term (directly

following the presentation), this knowledge was not maintained over the long term. However, the positive knowledge change measured during 2014 was not measured during 2016. In contrast, during 2016, a smaller percentage of growers understood the logic behind planting refuge or thought that planting refuge was necessary than during 2014. Despite this, a majority of growers still indicated that they understood the logic planting refuge. Future surveys are needed to determine if this trend of knowledge is declining over time. Increases in the categories of growers that did not understand the logic behind planting refuge and growers who did not think it was important to plant refuge were both significant from 2014 to 2016. Assuming that knowledge is correlated to willingness to plant refuge, this could indicate a reduction in refuge that is planted over time. However, this assumption may not be true and is likely nuanced. A simplistic framework is the profit maximizer argument (Livingston et al. 2007), where growers might maximize profit in the short term by planting Bt maize without refuge at the expense of creating resistance in the future. This model admittedly assumes that externalities are not associated with use of a pesticide (Hueth and Regev 1974), like Bt. However, externalities associated with the use of Bt could include areawide pest suppression (Hutchison et al. 2010), simplification of pest management, and reduction in overall foliar insecticide use (National Academies of Sciences, Engineering, and Medicine, 2016). Another framework acknowledges that growers who do not plant refuge can receive the benefit of pest suppression from those who do (Hutchison et al. 2010). Nonetheless, this becomes a tragedy of the commons when enough growers eschew planting refuge and resistance is created. Furthermore, while this model might apply to an insect pest like *O. nubilalis* in a relatively uniform agricultural system consisting of a Bt-producing host (maize) and a non-host (soybean), it may or may not apply to an insect pest such as *H. zea* in an environment dominated by two Bt-producing hosts (maize and cotton) and one non-Bt host (soybean). This issue becomes even more convoluted when one considers the marketing emphasis placed on Bt maize products for their control of pests that rarely limit yield (such as *H. zea*; U.S. EPA 1998), the unavailability for companion non-Bt hybrids from the same genetic background for all Bt hybrid families, and availability of non-Bt hybrids at the local dealer level for growers (as suggested by the results of Table 2). This can be a self-defeating problem, as seed companies do not breed for, or produce, hybrids that are not in demand, and as growers demand less non-Bt seed.

Additional survey questions in 2014 also probed grower acceptance for actions that might increase refuge compliance. The most popular of these two options, providing a rebate for purchasing non-Bt seed and providing non-Bt hybrids that yielded high relative to Bt hybrids, were pecuniary. The two least popular options to increase planting of refuge were a punitive option, yearly-on farm checks for refuge, and an option related to increasing the common resource pool by increasing neighboring farm compliance. Growers must already comply with refuge requirements when Bt seeds are purchased, and they can be subjected to field checks for refuge, although this is rarely done. Furthermore, many growers recognize the common resource pool of neighboring farms that plant non-Bt refuge. One subject of the 2014 presentation was based on a common grower question of the need to plant refuge if their neighbor had already done so.

There should be little to no yield penalty for planting a non-Bt refuge in timely planted North Carolina maize. North Carolina studies have shown that non-Bt and Bt hybrids from the same genetic background will yield equivalently and that *H. zea*, the most common insect pest, does not limit yield in timely planted maize (Reay-Jones and Reisig 2014). Furthermore, this information was made available to these growers in the year before the 2014 survey through various Extension outlets. Despite this finding, North Carolina grower perception is that non-Bt maize hybrids yield less than Bt maize hybrids even in the absence of insect pests or in the presence of *H. zea*. There could be many explanations for this, none of which are mutually exclusive, although all should be tested. One potential explanation is that growers observe this effect across a wide geography, and that this yield effect is not easily measured using typical university research small plots studies. A second explanation is that growers could be planting too much Bt maize because they are risk averse. For example, in North Carolina, *S. frugiperda* can be a yield limiting pest of maize, especially in later plantings. Although infestations are not usually widespread, they typically cause great yield loss in individual fields. Hence, although yield loss is rare, and not great on average, it can be great in the infested field. Another explanation could be that the belief in yield benefits has persisted from the pre-Bt era, when *O. nubilalis* and *Diatraea crambidoides* (Grote) were serious insect pests in North Carolina, but are now noticeably absent in non-Bt maize. Finally, as mentioned before, many of the Bt hybrids are marketed for their control of pests, such as *H. zea*, and many growers that purchase these seeds expect *H. zea* to be controlled.

Potential Targets to Increase Non-Bt Refuge Compliance

There were many significant correlations between environmental factors and both grower intentions to plant refuge and understanding the purpose and necessity of non-Bt maize refuge. Some of these factors are clearly collinear, such as farm size and net cash per farm, while others are likely collinear, such as total maize, cotton, soybean area and total cropland and farm size and total cropland. Despite this, some trends emerged, as total cropland and farm size were each correlated both to grower willingness to plant refuge and understanding about refuge. As previous studies have surmised (Kruger et al. 2009), smaller-sized growers are less likely to plant refuge. My survey indicates that this may be due, in part, to a dearth of understanding about the important and need for non-Bt refuge. Furthermore, this could be exploited as a way to target an increase in grower compliance, focusing attention on growers who farm in less agriculturally intensive areas, part time, or on smaller-sized farms.

The correlation between total cropland, farm size, etc., and refuge compliance, might explain why compliance was measured lower in this survey; North Carolina, like much of the Southeast, tends to have smaller-sized and more diverse farming systems than other agriculturally intensive areas of the Midwest, which are focused on maize and soybeans. Furthermore, ABSTC only surveys growers who plant at least 40 hectares of maize in the cotton-growing region, potentially missing many smaller-sized growers who are out of compliance. Future studies could test this hypothesis and could be coupled with an improved survey design that targets different groups of growers, farming systems, and follows individuals and their practices longitudinally. Moreover, new and creative Extension methods are needed beyond teaching about refuge using verbal presentations in county meetings, as these were ineffective in this study. Furthermore, no one action was identified by growers in this survey as an extremely popular option to increase refuge compliance. However, the suggested punitive action, yearly on-farm checks, was unpopular and, when applied on a large-scale and

targeting the likely uncompliant growers (*viz.*, the growers planting the least maize), will not be economically feasible (Bourget et al. 2005). Additionally, even though insecticide susceptibility is a common property resource and the U.S. EPA has determined that maintaining Bt susceptibility is in the "public good" (U.S. EPA 2001), much of the burden for ensuring refuge compliance has fallen upon the seed industry. Indeed, ABSTC surveys indicate that a majority of maize growers use their seed dealers as the primary source of information concerning refuge requirements; for example, 75% of growers indicated seed dealers as their primary source of information during 2015 (ABSTC 2016). Hence, in this framework, the seed industry could focus on the pecuniary, through more breeding, seed availability, and marketing efforts toward companion non-Bt refuge hybrids. This action was the most popular of the four suggested actions in the survey and should not be too burdensome for the seed industry to do, nor cause a yield penalty for North Carolina growers who can plant maize on time. This contrasts with much of the seed industry's past efforts to increase compliance through education using information provided by mailings, billboards, information on the maize seed bags, etc. (ABSTC 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016). Furthermore, recent efforts have been focused toward providing blended refuge, which are available for some toxin pyramids in the Midwest. For *H. zea*, a species of particular concern in the southern United States, a block refuge will delay resistance longer than a blended refuge (Caprio et al. 2015), but if refuge compliance is only 50%, a blended refuge is as good as, or better than a block refuge to delay resistance for this insect (Pan et al. 2015). Therefore, efforts should be placed into increasing block refuge compliance in southern United States if the goal of maintaining Bt susceptibility is to be achieved.

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