Corn Earworm (Lepidoptera: Noctuidae) in Northeastern Field Corn: Infestation Levels and the Value of Transgenic Hybrids

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ABSTRACT Corn earworm, *Helicoverpa zea* (Boddie), is a polyphagous noctuid pest of agricultural crops across the United States that is gaining attention as a pest of field corn. Before the introduction of transgenic insect-resistant hybrids, this pest was largely ignored in field corn, but now many *Bacillus thuringiensis* (Bt) corn hybrids have activity against corn earworm. However, the value of control in the northeastern United States is unclear because the risk posed by corn earworm to field corn has not been well characterized. To understand the threat from corn earworm and the value of Bt hybrids in field corn, we assessed corn earworm injury in Bt and non-Bt hybrids at 16 sites across four maturity zones throughout Pennsylvania in 2010, and 10 sites in 2011. We also used corn earworm captures from the PestWatch pheromone trapping network to relate moth activity to larval damage in field corn. Corn earworm damage was less than one kernel per ear at 21 of 26 sites over both years, and the percentage of ears damaged was generally <15%, much lower than in the southern United States where damage can be up to 30 kernels per ear. At sites with the highest damage levels, Bt hybrids suppressed corn earworm damage relative to non-Bt hybrids, but we found no differences among Bt traits. Cumulative moth captures through July effectively predicted damage at the end of the season. Currently, the additional benefit of corn earworm control provided by Bt hybrids is typically less than US$4.00/ha in northeastern field corn.

KEY WORDS *Helicoverpa zea*, transgenic corn, pheromone trap, *Bacillus thuringiensis*

Genetically modified corn (*Zea mays* L.) hybrids expressing insecticidal *Bacillus thuringiensis* (*Bt*) toxins were first planted commercially in the United States in 1996 (Burkness et al. 2011). Adoption rates have steadily increased since their introduction, resulting in the large-scale reduction of populations in the Midwest of at least one pest species, the European corn borer (*Ostrinia nubilalis* (Hübner); Hutchison et al. 2010). Populations of European corn borer in Pennsylvania may also be declining relative to historic populations, but it is unclear whether the suspected decline is driven by a similar mechanism (Bohnenblust et al. 2011). Recently, the number of transgenic events and hybrids commercially available has also increased and new hybrids may contain several genes targeting multiple insect pest species (Reay–Jones and Wiatrak 2011). Many Bt corn hybrids principally target one or two pest species, primarily the European corn borer, the western corn rootworm (*Diabrotica virgifera virgifera* (LeConte)), or both; however, hybrids can also target, or have varying activity on noctuid species, such as corn earworm, *Helicoverpa zea* (Boddie), fall armyworm, *Spodoptera frugiperda* (J.E. Smith), and western bean cutworm, *Striacosta albicosta* (Smith) (Horner et al. 2003a, b; Burkness et al. 2011).

Corn earworm is a noctuid species that feeds upon many crop species such as corn, cotton, soybean, tomato, and peppers (Rutschky 1950, Chitkowski et al. 2003, Nagoshi et al. 2009, Burkness et al. 2010, Molina–Ochoa et al. 2010, Westbrook and Lôpez 2010), and is an important pest of field corn in the southern United States (Buntin 2008). Corn earworm does not overwinter well in northern states, including Pennsylvania, but it annually recolonizes cold-weather states from the south (Blanchard 1942, Nagoshi et al. 2009, Changnon et al. 2010). Females are strongly attracted to silking corn and lay their eggs on silks (Johnson et al. 1975, Xinzhi et al. 2007, Buntin 2008). Because of its migratory habit and preference for silks, effective management tactics for sweet corn include planting early so that plants silk before its arrival (Buntin 2008), and timing insecticidal sprays based on moth captures in pheromone traps. These tactics, however, are not as relevant for field corn because of its longer growing season, and the lower value of grain as compared with sweet corn. Planting dates for field corn are planned to meet agronomic potential, and insecticidal applications to control corn earworm at the ear stage in field corn are logistically difficult because of crop height, large acreage, and the challenge of targeting larvae once they enter the husk; therefore, treatments

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are typically impractical and uneconomical (Buntin 2008).

Seed companies are now marketing Bt hybrids (e.g., Smartstax, Viptera) with increased insecticidal activity against corn earworm and other noctuid species (Dow Agrosciences 2010, Syngenta 2011). Before these newer hybrids, many Bt events (e.g., MON810) suppressed corn earworm populations by 70–90% (Kennedy and Storer 2000, Horner et al. 2003a). Now, hybrids containing several Bt events can offer near complete control of corn earworm (Burkness et al. 2010, Reay–Jones and Wiatrak 2011). However, this level of control is only relevant if populations of corn earworm pose an annual economic risk to field corn yield, and little research appears to have characterized damage of corn earworm in modern hybrids of field corn in northern states.

Flight activity of corn earworm moths can be used to time insecticide sprays for sweet corn and other vegetable crops. Individual growers can trap for moths to time their applications, or if they are in parts of the eastern United States, they can rely on shared data from the PestWatch system (Fleischer et al. 2007), a network of sex pheromone traps typically located on vegetable farms and managed by a suite of extension educators and other agricultural professionals. Data from this network are reported online (www.pestwatch.psu.edu) where it is freely available. Whereas the traps within the PestWatch network provide insight on population size and levels of activity, their utility as a predictive tool has been limited because the relationship between moth captures and plant damage is poorly understood.

In this article, we present 2 yr of data from field sites across Pennsylvania, quantifying corn earworm populations in plots planted with Bt and non-Bt field corn varieties. The goals of this research were to 1) quantify population levels of corn earworm and their damage in field corn in Pennsylvania, 2) assess the field-scale efficacy of Bt hybrids for controlling corn earworm, and 3) determine whether moth captures in the PestWatch network are predictive of the amount of damage found in corn fields at the end of the season.

Materials and Methods

Corn Earworm Population Assessments. To assess corn earworm damage in 2010 and 2011, we established replicated plots across Pennsylvania, in each of the state's four maturity zones (Fig. 1), which also extend into neighboring New York, New Jersey, and Maryland. In maturity zones 1, 3, and 4, we planted five Bt and five non-Bt hybrids, whereas six Bt and non-Bt hybrids were planted at sites in zone two (Tables 1 and 2). All Bt hybrids expressed at least one of the following lepidopteran active trait events and associated Bt proteins: Bt11-Cry1Ab; MON810-Cry1Ab; TC1507-Cry1 F; MON89034-Cry1A.105, Cry2Ab2; and MIR162-Vip3A. In 2010, we had plots on 14 commercial grain farms and two Penn State research farms (Table 1; Supp. Table 1 [available online only]). In 2011, we were limited to nine commercial farms and one research farm because of challenging weather conditions during planting, harvesting, or both (Table 1; Supp. Table 2 [available online only]). Experimental plots were arranged in a randomized complete block design within a larger commercial field, and each hybrid was replicated five times. At least four rows of corn were planted as a border to minimize edge effects, and no soil insecticides were used. Planting dates in 2010 ranged from 5 to 27 May in zone 1, 4–27 May in zone 2, 30 April through 17 May in zone 3, and 20–22 April in zone 4. In 2011, planting dates ranged from 1 to 3 June in zone 1, 26 May through 2 June in zone 2, 11 through 31 May in zone 3 and 7–12 May in zone 4. At all sites, commercial cooperators managed fertilizer and herbicide applications, and management tasks were typical of the region.

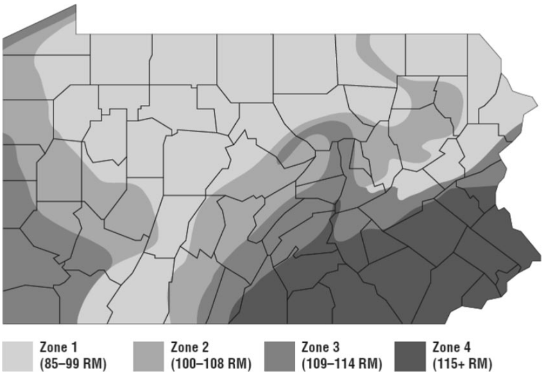

Fig. 1. Corn maturity zones in Pennsylvania and the approximate maximum relative maturity (RM) in days of hybrids for full-season grain production. Figure reproduced with permission from Penn State Extension (2011).

During September of each year, we assessed corn earworm damage on 10 ears per plot in four of the five replicates at each site. We recorded whether each ear was damaged, and measured the damaged area to the nearest 0.5 cm^2. Corn earworm damage was differentiated from damage caused by other pests by presence of larvae, location of damage, and how the ear was damaged. European corn borer often enters on the side or lower ear and also will tunnel into the ear, whereas corn earworm damage is most often evident on the ear tip and does not include tunneling into the cob. Damage caused by fall armyworm is generally indistinguishable from damage caused by corn earworm, however, few fall armyworm larvae (<5) were found over the course of both years, leading the authors to conclude that the majority of the damage was likely caused by corn earworm. Additionally, western bean cutworm is a pest new to Pennsylvania (Tooker and Fleischer 2010), and populations of this pest are generally low across the state so the likelihood of confusing western bean cutworm damage for corn earworm damage was low.

Corn Earworm Trapping. To assess the relationship between male moth captures in pheromone traps and corn earworm damage to field corn, we relied on data reported to PestWatch. Pheromone traps have been

Table 1. Maturity zones (county locations), trait events, and maturity of Bt hybrids grown in 2010 and 2011

Maturity zone	2010			2011		
	Hybrid	Trait events	Maturity (d)	Hybrid	Trait events	Maturity (d)
1 (2010 - Mercer, Tioga, Cambria, Bradford; 2011 - Mercer)	Chemgro 3000 GT	Bt11, MIR604, GA21	95	Chemgro 3000 GT	Bt11, MIR604, GA21	96
	Chemgro HXTRR2	TC1507, T25, DAS-59122–7	98	Chemgro HXTRR	TC1507, T25, DAS-59122–7	98
	Chemgro Exp[a] 3000 GT	Bt11, MIR604, GA21	95	Chemgro Exp 3000 GT	Bt11, MIR604, GA21	99
	TA Seeds CBLLRW	Bt11, MIR604	95	TA Seeds 3000 GT	Bt11, MIR604, GA21	95
	TA Seeds 3000 GT	Bt11, MIR604, GA21	99	TA Seeds Exp 3000 GT	Bt11, MIR604, GA21	99
2 (2010 - Centre, Indiana, Clinton, Westmoreland, Columbia; 2011 - Centre, Columbia, Indiana)	Chemgro VT3	MON810, MON88017	105	Chemgro 3000 GT	Bt11, MIR604, GA21	104
	ChemgroVT3	MON810, MON88017	105	Chemgro GSSTx	MON89034, MON88017, TC1507, DAS-59122–7	105
	TA Seeds Exp 3000 GT	Bt11, MIR604, GA21	103	TA Seeds Exp 3000 GT	Bt11, MIR604, GA21	103
	Chemgro Exp HXTRR2	TC1507, T25, DAS-59122–7	108	Chemgro Exp HXTRR2	TC1507, T25, DAS-59122–7	108
	TA Seeds 3000 GT	Bt11, MIR604, GA21	101	TA Seeds 3000 GT	Bt11, MIR604, GA21	101
	TA Seeds Exp 3000 GT	Bt11, MIR604, GA21	103	TA Seeds 3111 VIP	MIR162, Bt11, GA21, MIR604	103
3 (2010 - Clinton, Lycoming, Perry, Union; 2011 - Clinton, Lycoming, Dauphin)	Chemgro GSSTx	MON89034, MON88017, TC1507, DAS-59122–7	109	Chemgro GSSTx	MON89034, MON88017, TC1507, DAS-59122–7	109
	Chemgro VT3	MON810, MON88017	109	Chemgro VT3Pro	MON89034, MON88017	112
	Chemgro Exp 3000 GT	Bt11, MIR604, GA21	111	TA Seeds Exp 3111 VIP	MIR162, Bt11, GA21, MIR604	111
	TA Seeds HXT	TC1507, T25, DAS-59122–7	109	TA Seeds HXT	TC1507, T25, DAS-59122–7	109
	TA Seeds 3000 GT	Bt11, MIR604, GA21	111	TA Seeds 3000 GT	Bt11, MIR604, GA21	111
4 (2010 - York, Franklin, Lancaster; 2011 - York, Berks, Lehigh)	ChemgroVT3	MON810, MON88017	115	Chemgro 3000 GT	Bt11, MIR604, GA21	115
	Chemgro VT3	MON810, MON88017	114	Chemgro VT3	MON810, MON88017	114
	TA Seeds Exp 3000 GT	Bt11, MIR604, GA21	116	TA Seeds 3111 VIP	MIR162, Bt11, GA21, MIR604	114
	TA Seeds VT3	MON810, MON88017	115	TA Seeds VT3	MON810, MON88017	115
	TA Seeds VT3	MON810, MON88017	116	TA Seeds VT3	MON810, MON88017	116

[a] Exp refers to an experimental hybrid.

Table 2. Maturity zones, hybrid, and maturity of non-Bt hybrids grown in 2010 and 2011

Maturity zone	2010		2011	
	Hybrids	Maturity (d)	Hybrids	Maturity (d)
1	Chemgro GT	95	Chemgro GT	96
	Chemgro CV[a]	96	Chemgro CV	96
	TA Seeds Exp[b] LL	97	TA Seeds CV	97
	TA Seeds CV	95	TA Seeds CV	95
	TA Seeds GT	99	Chemgro Exp GT	99
2	Chemgro CV	107	Chemgro CV	104
	Chemgro CV	107	Chemgro CV	107
	TA Seeds Exp GT	103	TA Seeds GT	103
	Chemgro Exp RR	108	Chemgro Exp LL	108
	TA Seeds LL	101	TA Seeds LL	101
	TA Seeds CV	103	TA Seeds Exp RR	108
3	Chemgro CV	111	Chemgro CV	110
	Chemgro RR	112	Chemgro RR	112
	TA Seeds Exp GT	112	TA Seeds Exp CV	112
	TA Seeds LL	109	TA Seeds LL	109
	TA Seeds CV	111	TA Seeds CV	111
4	Chemgro RR	115	Chemgro RR	115
	Chemgro CV	118	TA Seeds Exp GT	115
	TA Seeds Exp GT	116	Chemgro Exp GT	116
	TA Seeds CV	115	TA Seeds CV	115
	TA Seeds RR	116	TA Seeds RR	116

[a] CV indicates a hybrid with no herbicide or Bt trait events.
[b] Exp refers to an exp hybrid.

used to track corn earworm populations as part of this system since 1998 (Fleischer et al. 2007). Each year, traps are established at many locations including ≈40 locations throughout Pennsylvania. Harstack wire cone traps were baited with corn earworm pheromone lures (Hercon Environmental, Emigsville, PA) and checked weekly beginning in June and ending in September. Pheromone lures were replaced every 2 wk. Traps were located on Penn State research farms in Centre (2010, 2011) and Lancaster Counties (2010), but otherwise were not located on the farm where field plots were located. To relate male captures to field corn damage at our field sites, we used data from the closest available trap or traps (up to three traps), which were located within the same county, except for Cambria and Columbia counties in 2010. Traps used for these two counties were located in Blair and Schuylkill counties, counties adjacent to Cambria and Columbia counties, respectively, and paired with sampling sites using global positioning system coordinates (Supp. Tables 1 and 3 [available online only]). For this analysis we excluded data from sites that did not have a trap in the same or adjacent counties. Ten of 16 sites in 2010 had a corn earworm trap in the same or adjacent county. The only location that did not have a corn earworm trap nearby in 2011 was the Mercer county farm. Traps were an average of 26.2 ± 4.5 km from damage evaluation sites in 2010, and 21.6 ± 5.4 km in 2011 (Supp. Table 3 [available online only]). The closest trap was 0.5 km and the farthest trap 61.3 km from their respective damage evaluation site across both years.

Statistical Analysis. For our corn earworm populations assessments, differences in larval infestations and amount of damage between Bt and non-Bt hybrids at all locations were combined and assessed using analysis of variance (ANOVA; SPSS 2010) with location and zone as random effects, and hybrid type as a fixed effect. The percentage of corn earworm-damaged ears was assessed using the same ANOVA model (SPSS 2010). Because our combined analysis detected interactions between treatment and among sites within zones, we assessed damage to ears, percent damaged ears, and the number of larvae per ear for each site using separate analyses (ANOVA; SPSS 2010). At the five sites where damage in Bt hybrids averaged above 0.15 cm^2, we assessed using ANOVA whether there were differences in the effectiveness of trait packages. Damage levels in Bt hybrids at other sites were too low to provide any meaningful differences between trait packages. Data were transformed $\log_{10}(x + 1)$ when necessary to satisfy the assumptions of ANOVA.

From PestWatch, we calculated cumulative moth captures through the end of July (approximate end of silking in field corn), through the first week in August, and the entire season, for traps appropriate for each of our sampling sites (Supp. Tables 1 and 3 [available online only]) and then related these cumulative captures to our field assessments of corn earworm populations in non-Bt hybrids (amount of damage per ear, and the percentage of ears damaged) using linear regression (SPSS 2010), with year as a covariate.

Results

Corn Earworm Damage Assessments. In 2010, we found corn earworm larvae actively feeding in ears at 7 of the 16 sites in September when we sampled plots. At these sites, densities of larvae per ear were never different between Bt and non-Bt hybrids (Table 3). Nevertheless, all the sites received some corn earworm damage, though in most cases injury was low. Only two counties (Westmoreland and Cambria) had damage that exceeded one kernel per ear (0.31–0.36 cm^2; Table 3). Despite these low levels of injury, Bt hybrids suffered significantly less damage from corn earworm than conventional hybrids at 8 of the 16 sites. At the two most heavily damaged sites, injury to Bt hybrids was ≈40% less than in non-Bt hybrids (Table 3). At these sites we detected no differences in the amount of damage among the different Bt trait combinations (Westmoreland: ANOVA $F_{2,18} = 0.821$, $P = 0.456$; Cambria: $F_{2,14} = 0.628$, $P = 0.548$; Table 4). When we considered the percentage of ears per sample that received some corn earworm damage, 9 of the 16 sites had significantly higher percentages in non-Bt plots than in Bt plots (Table 3). The percentage of ears damaged in non-Bt plots ranged from 0.5 to 32.5% and exceeded 10% at only four sites (Table 3). In Bt plots, the percentage of ears damaged exceeded 10% only in Westmoreland and Cambria Counties, but again Bt trait combinations performed similarly (Westmoreland ANOVA $F_{2,18} = 0.262$, $P = 0.772$; Cambria: $F_{2,14} = 0.737$, $P = 0.496$; Table 4).

In 2011, we detected less damage in Bt plots than non-Bt plots at 3 of 10 sites, where injury was 70% lower in Bt hybrids (Table 5). However, we did not

Table 3. Mean (±SEM) corn earworm damage per ear, larvae per ear, and percentage of ears damaged in Bt and non-Bt corn for sixteen locations in four different maturity zones across Pennsylvania in 2010

County	Type	Damage per ear (cm^2)	Larvae per ear	Percent damaged ears
Mercer	Bt	0.04 (0.03)[a]	0.00	1.00 (0.69)[a]
	Non-Bt	0.19 (0.05)[a]	0.00	7.50 (1.90)[a]
Tioga	Bt	0.08 (0.03)	0.00	1.67 (0.86)
	Non-Bt	0.12 (0.06)	0.00	4.00 (1.97)
Cambria	Bt	0.79 (0.14)[a]	0.03 (0.02)	19.00 (3.15)[a]
	Non-Bt	1.37 (0.15)[a]	0.04 (0.02)	32.50 (4.16)[a]
Bradford	Bt	0.00[a]	0.00	0.00[a]
	Non-Bt	0.21 (0.05)[a]	0.00	9.00 (2.98)[a]
Westmoreland	Bt	0.65 (0.09)[a]	0.01 (0.01)	17.50 (3.36)[a]
	Non-Bt	1.05 (0.19)[a]	0.01 (0.01)	31.67 (3.49)[a]
Centre	Bt	0.14 (0.08)	0.00	4.17 (1.58)
	Non-Bt	0.13 (0.05)	0.00	4.58 (1.52)
Indiana	Bt	0.13 (0.06)[a]	0.00	2.92 (1.27)[a]
	Non-Bt	0.34 (0.08)[a]	0.00	13.33 (1.82)[a]
Clinton	Bt	0.00[a]	0.00	0.00
	Non-Bt	0.05 (0.02)[a]	0.00	3.33 (1.77)
Columbia	Bt	0.02 (0.02)	0.00	1.25 (0.69)
	Non-Bt	0.06 (0.03)	0.01 (0.01)	2.50 (1.38)
Clinton	Bt	0.01 (0.01)	0.00	1.00 (1.00)
	Non-Bt	0.05 (0.03)	0.00	1.00 (0.69)
Lycoming	Bt	0.00	0.00	0.00
	Non-Bt	0.03 (0.03)	0.00	0.50 (0.50)
Union	Bt	0.00	0.00	0.00[a]
	Non-Bt	0.05 (0.03)	0.00	2.00 (0.92)[a]
Perry	Bt	0.01 (0.01)	0.00	0.50 (0.50)[a]
	Non-Bt	0.05 (0.02)	0.01 (0.01)	5.00 (1.70)[a]
York	Bt	0.06 (0.04)[a]	0.01 (0.01)	2.50 (1.60)[a]
	Non-Bt	0.27 (0.06)[a]	0.01 (0.01)	13.50 (3.50)[a]
Lancaster	Bt	0.00[a]	0.00	0.00[a]
	Non-Bt	0.16 (0.05)[a]	0.02 (0.02)	9.50 (2.76)[a]
Franklin	Bt	0.05 (0.04)	0.01 (0.01)	1.50 (0.82)
	Non-Bt	0.18 (0.11)	0.01 (0.01)	5.50 (2.11)

[a] Mean within a column within each site significantly different at $\alpha = 0.05$. For full statistics see Supp. Table 1 (available online only).

detect differences in damage reduction among Bt trait combinations at these three sites where corn earworm populations were highest (Indiana: ANOVA $F_{3,17} = 2.144$, $P = 0.132$; Centre: $F_{3,17} = 1.532$, $P = 0.242$; Lehigh: $F_{2,14} = 1.438$, $P = 0.270$; Table 4). At the remaining seven sites, corn earworm damage was low (less than one kernel per ear) or absent.

The three counties that experienced lower damage levels per ear in Bt than non-Bt hybrids also had a lower percentage of ears damaged in Bt plots (Table 5). The percentage of ears damaged in Bt hybrids was never higher than 8%, whereas non-Bt hybrids exceeded 10% at three sites with a maximum of 32% of ears damaged in Indiana County. In Indiana County,

Table 4. Mean (±SEM) corn earworm damage per ear, the percentage of damaged ears in hybrids with different Bt trait packages for five locations with the highest corn earworm damage levels in Pennsylvania in 2010 and 2011

County, year	Trait package	Damage per ear (cm^2)	Percent damaged ears
Cambria, 2010	Bt11, MIR604, GA21	0.75 (0.29) a	18.33 (3.66) a
	Bt11, MIR604	1.23 (0.69) a	25.0 (11.90) a
	TC1507, T25, DAS-59122–7	0.49 (0.26) a	15.00 (2.89) a
Westmoreland, 2010	Bt11, MIR604, GA21	0.58 (0.15) a	17.69 (4.82) a
	TC1507, T25, DAS-59122–7	0.63 (0.24) a	12.50 (4.79) a
	MON810, MON88017	0.86 (0.24) a	20.00 (6.27) a
Indiana, 2011	Bt11, MIR604, GA21	0.371 (0.105) a	8.33 (1.67) b
	MON89034, MON88017, TC1507, DAS-59122–7	0.400 (0.400) a	2.50 (2.50) ab
	TC1507, T25, DAS-59122–7	0.775 (0.249) a	20.00 (4.08) c
	MIR162, Bt11, GA21, MIR604	0.00a	0.00a
Centre, 2011	Bt11, MIR604, GA21	0.19 (0.11) a	6.67 (3.33) a
	MON89034, MON88017, TC1507, DAS-59122–7	0.00a	0.00a
	TC1507, T25, DAS59122–7	0.55 (0.35) a	10.00 (4.08) a
	MIR162, Bt11, GA21, MIR604	0.00a	0.00a
Lehigh, 2011	Bt11, MIR604, GA21	0.46 (0.46) a	10.00 (10.00) a
	MIR162, Bt11, GA21, MIR604	0.01 (0.01) a	2.50 (2.50) a
	MON810, MON88017	0.10 (0.06) a	4.17 (1.93) a

Within a site and year, values labeled with different letters are significantly different ($P < 0.05$; see text for details on statistics).

Table 5. Mean (±SEM) corn earworm damage per ear, larvae per ear, and percentage of damaged ears in Bt and non-Bt corn for 10 locations in four different maturity zones across Pennsylvania in 2011

County	Type	Damage per ear (cm^2)	Larvae per ear	Percent damaged ears
Mercer	Bt	0.04 (0.03)	0.00	2.00 (1.56)
	Non-Bt	0.07 (0.02)	0.00	4.50 (1.35)
Centre	Bt	0.19 (0.08)[a]	0.00	3.75 (1.57)[a]
	Non-Bt	0.69 (0.15)[a]	0.01 (0.01)	15.00 (2.62)[a]
Indiana	Bt	0.38 (0.09)[a]	0.02 (0.01)	7.92 (1.70)[a]
	Non-Bt	1.29 (0.20)[a]	0.03 (0.01)	29.17 (3.06)[a]
Columbia	Bt	0.02 (0.01)	0.00	0.42 (0.42)
	Non-Bt	0.15 (0.07)	0.00	2.11 (1.04)
Clinton	Bt	0.09 (0.05)	0.00	2.50 (1.23)
	Non-Bt	0.11 (0.09)	0.00	2.51 (1.76)
Lycoming	Bt	0.03 (0.01)	0.00	3.00 (1.05)
	Non-Bt	0.03 (0.02)	0.00	2.50 (1.60)
Dauphin	Bt	0.00	0.00	0.00
	Non-Bt	0.00	0.00	0.00
York	Bt	0.00	0.00	0.00
	Non-Bt	0.01 (0.01)	0.00	1.10 (0.76)
Berks	Bt	0.03 (0.02)	0.00	1.50 (1.09)
	Non-Bt	0.12 (0.06)	0.01 (0.01)	5.90 (2.11)
Lehigh	Bt	0.16 (0.10)[a]	0.00	5.00 (2.24)[a]
	Non-Bt	0.54 (0.16)[a]	0.01 (0.01)	15.50 (3.12)[a]

[a] Mean within a column within each site significantly different at $\alpha = 0.05$. For full statistics see Supp. Table 2 (available online only).

we detected a significant difference among the trait combinations in the percentage of ears damaged ($F_{3,17} = 8.594$; $P = 0.001$); hybrids with the MIR162, Bt11, GA21, and MIR604 event combination expressing the Vip3A protein were most effective for reducing the number of damaged ears (Table 4). At this same site, hybrids expressing the Cry1F toxin (TC1507 event) had higher rates of ear damage than hybrids expressing other traits, while hybrids expressing the Cry1Ab toxin (Bt11 event) were better at reducing damage than hybrids expressing the Cry1F toxin, but worse than hybrids expressing the Vip3A toxin. At the Centre and Lehigh County sites, we did not detect differences among trait combinations for the percentage of ears damaged (Centre: ANOVA $F_{3,17} = 1.318$, $P = 0.301$; Lehigh $F_{2,14} = 0.787$, $P = 0.475$; Table 4). While not statistically distinct, we found no ear damage in hybrids expressing the Vip3A protein at the three sites with high corn earworm pressure in 2011 (Table 4). Larvae were only found at four sites in 2011 and larval densities per ear were low and never significantly different between Bt and non-Bt (Table 5). In both years, as would be expected, we observed the majority of damage near the tip, with damage occurring infrequently on other parts of the ear.

Relationship Between Moth Captures and In-Field Populations of Corn Earworm. The end of July approximately coincides with the end of field-corn silking in our area, and silking corn is the most attractive host of corn earworm (Johnson et al. 1975). Cumulative corn earworm male captures through the month of July were positively associated with both the amount of damage per ear (Table 6; Fig. 2), and the percentage of ears damaged in non-Bt hybrids (Table 6; Fig. 3). Male captures through the first week in August were also positively associated with damage and the percentage of ears damaged, but this relationship was weaker than captures through the end of July (Table 6). Cumulative capture through the entire season was not related to damage or the percentage of ears damaged (Table 6). Notably, season long cumulative moth captures were higher in 2010 than 2011, but cumulative captures through July were higher in 2011 (Table 7).

Discussion

During both years, damage caused by corn earworm in field corn across Pennsylvania was generally low. In non-Bt plots, which can be used as indicators of population size, only three sites over 2 yr had damage levels above 1 cm^2 (equivalent to ≈3 kernels/ear damaged). Corn kernels range in size from ≈0.31–0.36 cm^2, therefore, damage across the state spanned 0.0–4.4 kernels/ear, with yield loss estimates ranging from 0.0 to 90.6 kg/ha. By comparison, a yield loss of 62.4

Table 6. Linear regressions between the no. of corn earworm adults captured in monitoring traps and the amt of damage (cm^2), and the percentage of ears damaged in non-Bt field corn

Capture endpoint	Y	Model	F	R^2	P
31 July	Damage (cm^2)	$Y = 0.006X - 0.14$	13.943	0.45	0.002
	% ears damaged	$Y = 0.129X - 1.01$	10.60	0.38	0.005
7 Aug.	Damage (cm^2)	$Y = 0.003X - 0.03$	6.726	0.28	0.019
	% ears damaged	$Y = 0.086X + 0.48$	7.393	0.30	0.015
Full season	Damage (cm^2)	$Y = 0.00004X - 0.32$	0.11	0.01	0.748
	% ears damaged	$Y = 0.002X + 8.31$	0.52	0.03	0.480

Models for 31 July correspond to Figs. 2 and 3.

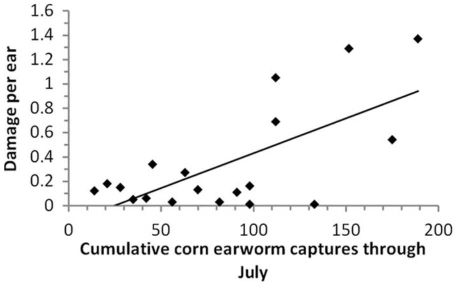

Fig. 2. Linear regression between corn earworm male captures in pheromone traps through the end of July and the amount of damage per ear (square centimeters) because of corn earworm in non-Bt hybrids ($Y = 0.006X - 0.14$; $R^2 = 0.45$; $P = 0.002$).

kg/ha (one bushel per acre) is expected if an acre of corn had a uniform infestation and three kernels were lost per ear (i.e., 90,000 kernels per bushel at a 30,000 ears per acre density; Lee and Herbek 2005). Notably, non-Bt hybrids at 14 of 16 sites in 2010 and seven of 10 sites in 2011 experienced damage equal to or less than one kernel per ear. Estimated yield loss at these sites would have been equivalent to between 0.0–20.6 kg/ha. These low levels of injury in non-Bt hybrids may indicate that corn earworm populations or oviposition rates in our fields were low, husk characteristics of non-Bt field corn hybrids may suppress some corn earworm damage, or that there are other mortality factors that kept damage rates low in both non-Bt and Bt hybrids. Longer tighter husks have been shown to reduce corn earworm damage (Ditman and Cory 1933), and newer field corn hybrids may have longer and tighter husks compared with sweet corn and older varieties grown in the early 20th century.

The low populations we encountered are noteworthy because in 2010 and 2011, regional moth captures in pheromone traps detected substantial flight levels for Pennsylvania (Table 7). Moreover, sweet corn fields on two of the farms that hosted our plots these years experienced substantial damage from corn earworm. In replicated untreated controls, average damage rates on sweet corn ears were 64 and 98% in Centre and Lancaster Counties, respectively, in 2010, and 20% in Centre County in 2011 (S.F., unpublished data). In those trials, the damage was caused mostly by corn earworm in Centre County in 2010 and from a mix of corn earworm and European corn borer in the other years and locations. Planting date might play a role in the higher amounts of damage in these sweet corn trials as they were planted in mid-June whereas the latest our field corn was planted was 2 June. Nevertheless, our results indicate that even in years with heavy adult corn earworm activity, damage in field corn fields using current hybrids and planting dates is inconsistent, thus corn earworm may not normally be a serious pest in field corn in our area. By comparison, in the southeastern United States, corn earworm captures in pheromone traps are much higher, ranging from ≈30 moths per week in May to over 800 moths per week at the end of July (Greene 2010). Further, ear damage in non-Bt hybrids because of corn earworm can be three to five times higher than the highest levels we observed in Pennsylvania during 2010 and 2011 (Reay–Jones and Wiatrak 2011). Historical damage levels in the southeastern United States were even higher ranging from 15 to 30 kernels/ear in early versus late planted corn (Phillips and Barber 1934).

When corn earworm did infest a field at damaging levels, Bt hybrids suppressed damage. Damage in Bt plots did not exceed 0.80 cm^2, and tended to be lower than damage in non-Bt hybrids (Table 3). At the five sites where corn earworm damage was highest, it was ≈40% lower in 2010 and 70% lower in 2011 in Bt than in non-Bt, similar to previous reports (Sedlacek et al. 2009, Buntin 2010, Reay–Jones and Wiatrak 2011). Unexpectedly, we did not detect substantial differences in effectiveness among Bt trait combinations. Nevertheless, we found no damage on hybrids expressing the Vip3A toxin, suggesting that this toxin is very effective for controlling corn earworm damage, consistent with other studies (Burkness et al. 2010; Table 4). The lack of statistical differences among trait combinations appears to contradict previous reports (Reay–Jones and Wiatrak 2011); however, the damage levels we found in these 2 yr in Pennsylvania were quite low, perhaps obscuring the influence of the different traits. In fact, the highest levels of damage in our non-Bt hybrids were similar to amounts of damage detected in the most effective Bt hybrid in South Carolina (Reay–Jones and Wiatrak 2011), suggesting that infestation levels likely play a key role in the efficacy and value of trait combinations.

Given the low in-field populations of corn earworm that we found over 2 yr, it would be difficult to justify specifically targeting corn earworm with Bt field corn hybrids in the area studied. However, in Pennsylvania, Bt hybrids are often planted for control of European corn borer, so corn earworm control is an additional benefit of planting Bt hybrids. We surveyed local seed dealers, and seed for the Bt hybrids planted in our study carried a $50/ha premium above non-Bt seed. At the current price of corn (US$0.24–0.28 /kg; National Agriculture Statistics Service [NASS] 2012a) growers would need to avoid insect damages that cause an average yield loss of 178.6–208.4 kg/ha for Bt hybrids

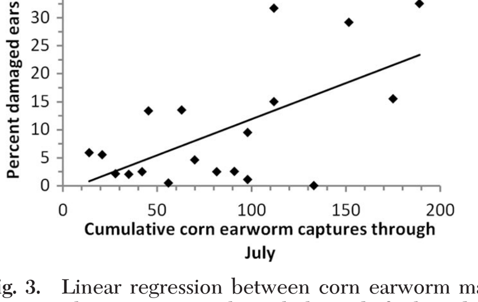

Fig. 3. Linear regression between corn earworm male captures in pheromone traps through the end of July and the percentage of damaged ears because of corn earworm in non-Bt hybrids ($Y = 0.129X - 1.01$; $R^2 = 0.38$; $P = 0.005$).

Table 7. Cumulative corn earworm adult captures in pheromone traps at sites in the Pestwatch monitoring network with sister sites where damage evaluations occurred in 2010 and 2011

Location	2010		2011	
	Captures through July	Total yearly captures	Captures through July	Total yearly captures
Cambria[a,b]	189 (46)	1,066 (338)		
Westmoreland[a]	112 (21)	665 (49)		
Centre	70	2,800	112	441
Indiana[a]	46 (25)	459 (25)	152 (24)	194 (10)
Columbia[c]	42	378	28	49
Union	35	105		
Clinton			91	105
Lycoming[a]	56 (11)	532 (186)	82 (16)	189 (8)
Dauphin			133	133
York	63	1,540	98	896
Franklin[a]	21 (0)	109 (39)		
Lancaster	98	1,652		
Berks			14	231
Lehigh			175	2,450

Empty cells indicate there was either no damage evaluation or no trap that year.
[a] Several traps were present so captures are represented by a mean (±SE).
[b] Traps were in Blair County.
[c] Trap was in Schuylkill County in 2010.

to be profitable. With the damage we measured, yield loss caused by corn earworm would rarely exceed 62.4 kg/ha indicating that farmers would need to have yield losses of 116–146 kg/ha from insect pests other than corn earworm to make planting Bt hybrids profitable. Based on damage levels at our sites, the estimated value of planting Bt hybrids for corn earworm control over both years ranged from US$0.00–16.91/ha, but was less than US$4.00/ha at 20 of 26 sites over both years (Figs. 4 and 5). Additionally, reducing ear feeding by corn earworm may reduce *Aspergillus* and *Fusarium* rots associated with corn earworm damage, reducing the risk of mycotoxin contamination, resulting in better grain quality (Widstrom et al. 1975, Smith and Riley 1992, Horner et al. 2003a). If a farmer experiences significant damage from other pest species or the risk of ear rots is high, they would see additional benefits from planting Bt hybrids in the form of reduced damage cause by corn earworm.

While the infestations we measured in Pennsylvania corn fields indicate that corn earworm is currently a minor pest of field corn, this situation could change. At present corn earworm does not appear to overwinter in Pennsylvania, but can survive winter in the mid-Atlantic, south of the 40th parallel (Diffenbaugh et al. 2008, Morey et al. 2012), which traverses southern Pennsylvania. Because southern Pennsylvania appears to be at the northerly edge of its overwintering range, small changes to regional climate may influence regional populations of corn earworm (Diffenbaugh et al. 2008). Moreover, given that some models of global climate change predict that the climate of Pennsylvania in 50 yr could resemble the current climate of North Carolina (Union of Concerned Scientists 2008), it appears possible that corn earworm may become a more serious pest in Pennsylvania field corn in the coming decades. If corn earworm does become a more serious pest, the economic benefit of Bt hybrids will likely increase.

Although the PestWatch trapping and reporting system was designed to help provide management information for growers of sweet corn and other vegetables, and sites were located on vegetable farms, we found male moth capture to be a significant predictor of corn earworm damage in field corn (Figs. 1 and 2). The statistical relationships between the total number of male moths trapped through the end of July and in-field damage rates were quite robust. Other trapping intervals yielded weaker relationships, perhaps

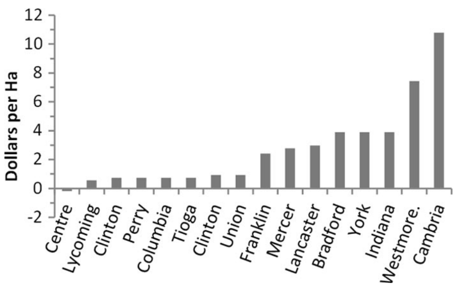

Fig. 4. Estimated value (dollars per hectare) of corn earworm control provided by Bt hybrids at each site in 2010 assuming a kernel size of 0.31 cm^2, a corn price of US$0.28/kg, and a US$50/ha premium for Bt seed.

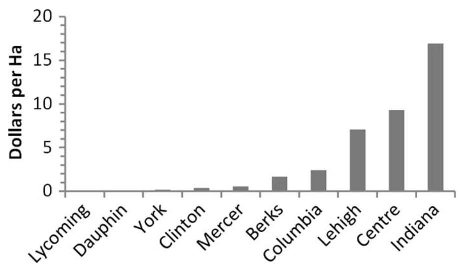

Fig. 5. Estimated value (dollars per hectare) of corn earworm control provided by Bt hybrids at each site in 2011 assuming a kernel size of 0.31 cm^2, a corn price of US$0.28/kg, and a US$50/ha premium for Bt seed.

because total moth flight through July is the portion of the population most strongly responding to silking field corn, the preferred oviposition site. We are not aware of previous research that has found a similar linear relationship between captures of males and in-field damage rates in field corn in the eastern United States. One study from sweet corn in the western United States, however, found that field infestations of corn earworm were related to date of silking and moth capture in pheromone traps (Coop et al. 1992). Thus, it appears that the PestWatch system can provide farmers and the seed industry with a reliable assessment of overall damage levels at the end of the season, which may suggest that more targeted placement of traps near field corn acreage would be warranted. While unlikely to change in-season management in field corn, because of logistical challenges associated with this high-acreage crop, moth captures can indicate the size of corn earworm populations and provide insight on whether year-to-year risk from corn earworm is increasing. If this risk grows larger, it would make economic sense to target corn earworm in the coming years with Bt hybrids.

It is important to note that corn earworm populations migrating north are strongly dependent on populations that develop on plant hosts in southern or western agricultural fields. Because insect populations tend to track preferred host availability and abundance, corn is likely to drive corn earworm populations as it is the preferred host (Molina–Ochoa et al. 2010). Adoption rates of Bt corn in the southern United States have traditionally been lower than in other parts of the country due, in part, to Environmental Protection Agency (EPA) regulations mandating 50% of corn acreage be a non-Bt refuge. Recently, however, EPA reduced refuge size in the South for some Bt corn hybrids to 20%, likely resulting in an increase in Bt corn acreage that will be planted in the southern United States (Hutchison and Storer 2010). This expected increase in Bt corn acreage may influence pest abundance as has been seen in the Midwest (Hutchison et al. 2010), but in the South cotton, sorghum, soybean, and peanut will also play a large role in determining corn earworm (aka cotton bollworm) abundance (Jackson et al. 2008). Cotton, similar to corn, has been modified to express Bt toxins for insect control, and many Bt cotton cultivars have activity against corn earworm. Estimates of Bt cotton adoption are as high as 33% for insect-resistant only varieties, and 84% for stacked herbicide and insect resistant varieties in some states, and 63% across the United States (Chitkowski et al. 2003, Greenberg and Adamczyk 2010, NASS 2012b), therefore, corn earworm flights to northern states and associated damage will depend on hybrid selection and performance of Bt varieties of corn and cotton and the amount of non-Bt acreage along with the abundance of other hosts.

In summary, the data that we present here suggest that for the past two seasons, corn earworm damage in field corn in Pennsylvania was only sufficient to justify marginal additional seed costs for Bt hybrids that provide stronger control. If corn earworm populations increase with climate change and overwintering occurs farther north or if adoption rates of Bt cotton and corn in the southern United States change, corn earworm populations in Pennsylvania field corn may change, altering the value of corn earworm control. Our results also demonstrate that field-level damage from corn earworm in northern states may be predicted by male moth captures reported in the PestWatch pheromone trapping network. Researchers, extension educators, and growers may be able to use these moth captures in-season to help determine the potential economic benefit of corn earworm control from Bt hybrids. Future decisions may also rest on long-term moth-capture; this network may play an important role in determining whether corn earworm flights are high enough annually to justify targeting corn earworm with Bt hybrids in northeastern agroecosystems.

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