Supplementary Information Appendix

Regional pest suppression associated with widespread Bt maize adoption benefits vegetable growers

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SI Supplementary Text - Materials and Methods

Transgenic corn adoption and environmental data

We obtained data on the actual percentage of total corn acreage planted in Bt hybrids for each mid-Atlantic crop-reporting district (CRD; for 2002, 2006 and 2013) from the Agricultural Biotechnology Stewardship Technical Committee (ABSTC). These data were derived from Bt corn seed sales records submitted each year by the Bt technology companies to the U.S. Environmental Protection Agency, and may not accurately represent the cropping districts that the seeds were ultimately planted in. In addition to Bt adoption in the CRD, we also used the national average percentage of planted Bt corn acres (1) as a predictor of trends in moth populations. Previous reports identify the role of temperature and precipitation on the population dynamics of *Ostrinia nubilalis* and *Helicoverpa zea*, and increased feeding and crop damage (2–4). To add these environmental factors to our analyses, we downloaded average temperature and precipitation data during the growing seasons (April–September) of the study period (1976–2016), for the climatic divisions corresponding to each CRD, from NOAA— National Centers for Environmental Information (http://www.ncdc.noaa.gov/cag/time-series).

Statistical analyses

Trends in moth captures and recommended insecticide treatments

We compared the trends during Pre-Bt (1976-1995), and Bt years (1996-2016) for average daily moth captures by year, and the number of recommended insecticide treatments in each vegetable crop through piecewise linear mixed-effects models using restricted maximum likelihood. Individual piecewise linear mixed-effects models were run with the log-transformed moth captures data for each species (*O. nubilalis*, *H. zea*), and the number of recommended insecticidal treatments in each vegetable crop (peppers, green beans, sweet corn) as the response variable. Year was included as fixed effect partitioned into intervals (Pre-Bt and Bt years) to fit separate line segments, and CRD as random effect (random intercept) to account for repeated measurement.

Benefits of Bt corn for vegetable crops

For Bt years, we analyzed average moth captures and recommended insecticide treatments as a function of Bt adoption each year and as a function of environmental factors, through linear mixed-effects models using restricted maximum likelihood. For each moth species, we ran separate linear mixed-effects models. As exploratory analysis for moth captures data, we first ran an initial full model that included all the individual and interactive effects of Bt corn adoption (separate models Bt corn % in CRD, and national Bt corn %), temperature and rainfall as predictors. We ranked the candidate models based on Akaike Information Criteria corrected for small sample sizes (AICc) (5), and selected the best model among top two based on chi-square tests on the log-likelihood values (see Tables S5-S8 for exploratory analysis summary). For *O. nubilalis*, models included log transformed average moth captures as response, additive effects of Bt adoption (separate models for Bt corn % in CRD and national Bt corn % as predictors), temperature, and precipitation as fixed effects, and CRD as random effect to account for repeated measurement. For *H. zea*, the model parameters were similar except that precipitation was not included as a predictor in the final model as per the model selection procedure.

For the linear mixed-effects models analyzing recommended insecticide treatments for each moth pest in each vegetable crop, only Bt adoption (separate models for Bt corn % in CRD and national Bt corn %) was used as a predictor. We ran regression analysis with the total insecticides applied in peppers and sweet corn in New Jersey as a function of national Bt corn adoption. For trends in *O. nubilalis* damage, we first compared the square root transformed damage data between Pre-Bt and Bt corn years through ANOVA, and performed regression on damage during Bt years a function of Bt corn adoption.

We determined the statistical significance of the fixed effects in the linear mixed-effects models through Wald *F* tests with Kenward-Roger approximation. As a measure of the proportion of total variance explained, we calculated $\boldsymbol{R}_{\beta}^{2}$ value, including partial-$\boldsymbol{R}_{\beta}^{2}$ wherever applicable, defined through Kenward-Roger approximation for the linear mixed-effects models (6). We ensured model appropriateness through diagnostic plots of the models visualizing within-group residuals (standardized residuals Vs fitted values, normal Q-Q plots, histograms of residuals) and estimated random effects (normal Q-Q plots and pairs-scatter plot matrix) (7). Linear mixed-effects models were constructed with package ‘lme4’ (8) and ranked based on AICc values using package ‘MuMIn’ (9). Wald *F* tests were performed with package ‘car’ (10), and $\boldsymbol{R}_{\beta}^{2}$ value were generated with package ‘r2glmm’(11). Estimated coefficients were extracted and plotted using “ggplot2” (12), all in R program (13).

SI Supplementary Figures

Figure S1. Blacklight trap locations across the agricultural crop-reporting districts in mid-Atlantic United States. Inset map shows the study area in the east coast of United States.

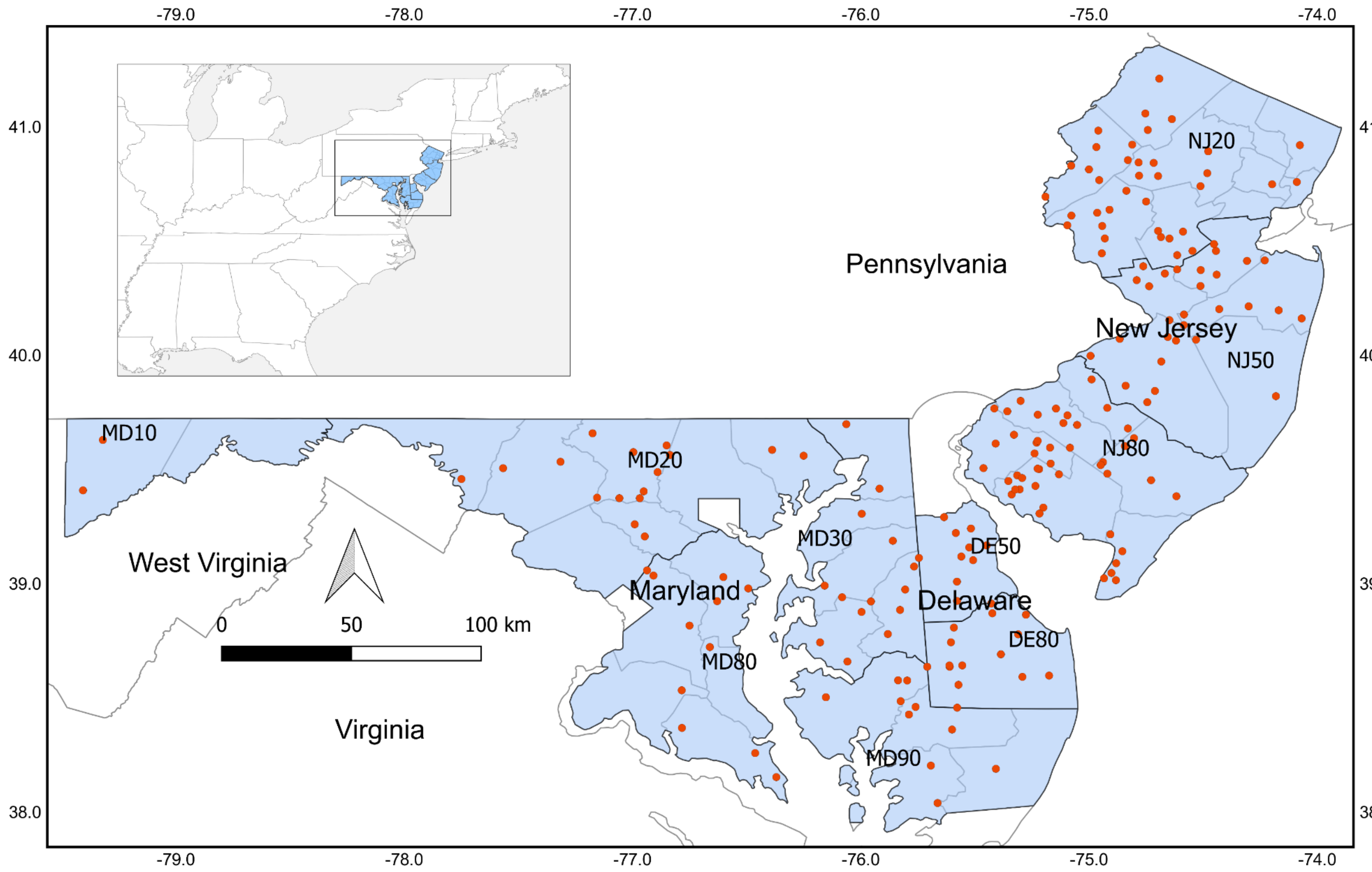
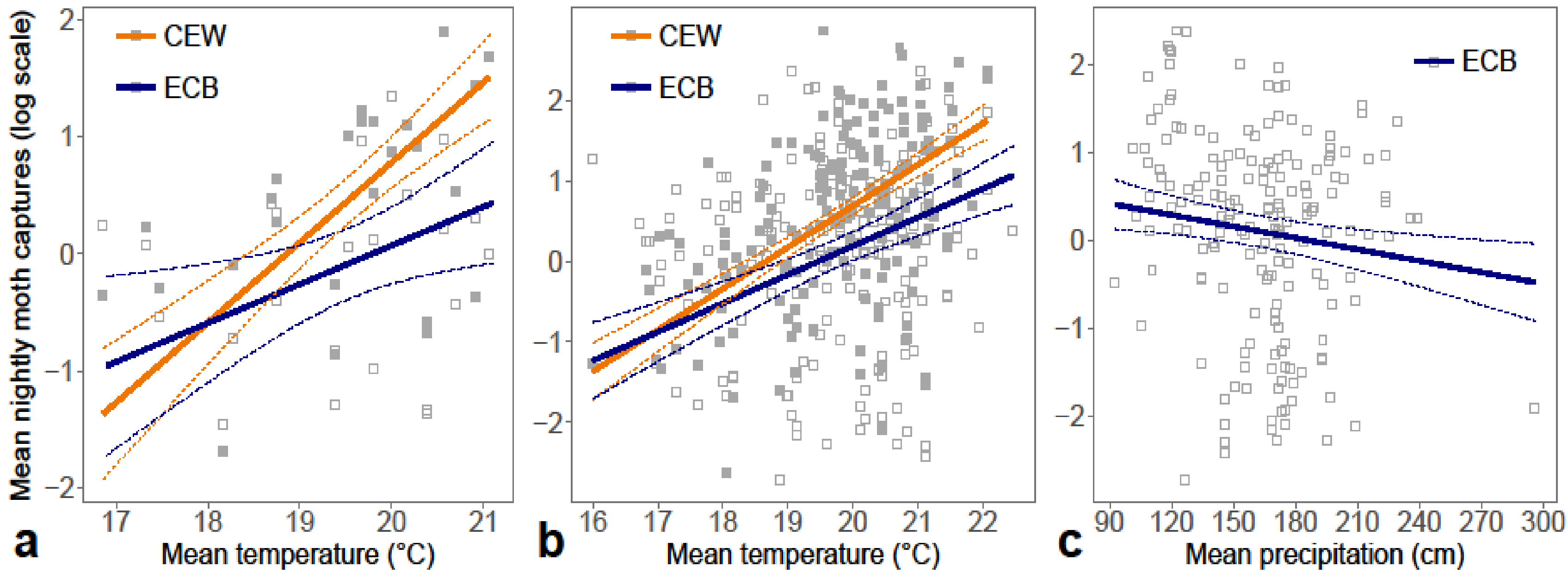


Figure S2. Mean nightly moth captures in mid-Atlantic United States (1996-2016 as a function of environmental factors.

Positive linear relationship between mean nightly moth captures and temperature based on models that included additive effects of (**a**) Bt corn in crop-reporting districts and (**b**) national average Bt corn. (**c**), Negative linear relationship between temperature and mean nightly *Ostrinia nubilalis* (ECB) captures based on model that included additive effects of national average Bt corn. Predictions from linear mixed-effects models are plotted (dark lines) along with upper and lower confidence levels (95% CI; dotted lines) while points represent average yearly moth captures (ECB – blue lines and open squares; *Helicoverpa zea* (CEW) – orange line and grey squares), all in logarithmic scale.



SI Supplementary Tables

Table S1. Summary of the blacklight trap monitoring networks operating in Delaware, Maryland and New Jersey during 1976-2016.

Details are given on the mean number of trap locations and data years that provided time-series information during June 13 to September 17 for each moth species.

State	Crop reporting district	Mean no. of traps operating per year[1]	*Ostrinia nubilalis* European corn borer		*Helicoverpa zea* Corn earworm	
			No. of data years[2]	Range of years	No. of data years[2]	Range of years
Delaware	DE 50	3.4	33	1976-2016	33	1976-2016
	DE 80	6.1	33	1976-2016	33	1976-2016
Maryland	MD 10	2.6	30	1980-2009	30	1980-2009
	MD 20	9.8	34	1976-2009	34	1976-2009
	MD 30	11.9	34	1976-2009	34	1976-2009
	MD 80	6.3	34	1976-2009	34	1976-2009
	MD 90	5.2	38	1976-2013	37	1976-2014
New Jersey	NJ 20	17.3	27	1978-2016	19	1998-2016
	NJ 50	15.0	27	1978-2016	19	1998-2016
	NJ 80	16.1	27	1978-2016	20	1990-2016

[1]Number and location of operational traps in each crop-reporting district varied among years.
[2]Data were not available for all years within the given range.

Table S2. Analysis of pest moth activity trends in Mid-Atlantic United States (1976-2016), and its association with Bt corn adoption.

Pest	n	Fixed effects	Coefficient estimate	Std. Error	Wald F	DF	Resid. DF	p-value	R_{β}^{2}
Trends in nightly moth captures									
Ostrinia nubilalis	317	Intercept	1.42	0.14					0.62
		Pre-Bt years (1976-1995)	-0.01	0.01	2.58	1	306.9	0.109	0.008
		Bt years (1996-2016)	-0.14	0.01	321.73	1	309.0	<0.0001	0.50
Helicoverpa zea	293	Intercept	1.54	0.22					0.36
		Pre-Bt years (1976-1995)	0.01	0.01	0.70	1	281.5	0.403	0.002
		Bt years (1996-2016)	-0.10	0.01	108.86	1	286.9	<0.0001	0.29
Moth captures as a function of national average Bt corn, and environmental factors									
Ostrinia nubilalis	179	Intercept	-4.58	1.22					0.78
		Bt corn (%)	-0.04	0.00	322.89	1	164.50	<0.0001	0.66
		Mean temperature (°C)	0.36	0.06	31.95	1	32.32	<0.0001	0.50
		Mean precipitation (cm)	-0.004	0.00	7.98	1	171.82	0.005	0.04
Helicoverpa zea	172	Intercept	-8.42	0.88					0.57
		Bt corn (%)	-0.03	0.00	141.82	1	137.29	<0.0001	0.47
		Mean temperature (°C)	0.51	0.05	119.17	1	15.52	<0.0001	0.43
Moth captures as a function of Bt corn in crop-reporting district, and temperature									
Ostrinia nubilalis	26	Intercept	-5.12	2.43					0.71
		Bt corn (%)	-0.03	0.00	43.64	1	20.70	<0.0001	0.68
		Mean temperature (°C)	0.33	0.13	5.81	1	14.14	0.030	0.29
Helicoverpa zea	26	Intercept	-11.80	1.97					0.72
		Bt corn (%)	-0.03	0.00	39.45	1	22.73	<0.0001	0.64
		Mean temperature (°C)	0.70	0.11	39.69	1	11.69	<0.0001	0.67

Table S3. Analysis of the number of insecticidal sprays per crop cycle in vegetable crops in mid-Atlantic United States (1976-2016), and its relationship with Bt corn adoption.

Results from linear mixed-effects models with number of insecticidal sprays as response variable. Values of R^2_β are the proportions of total variance explained by the entire model (intercept) or for each predictor.

Pest	**Crop**	**n**	**Fixed effects**	**Coefficient estimate**	**Std. Error**	**Wald F**	**DF**	**Resid. DF**	***p*- value**	R^2_β
Trends in number of recommended insecticidal sprays										
Ostrinia nubilalis	Peppers	317	Intercept	5.50	0.83					0.35
			Pre-Bt years (1976-1995)	-0.04	0.02	3.04	1	305.3	0.08	0.009
			Bt years (1996-2016)	-0.20	0.02	99.07	1	305.7	<0.0001	0.23
	Green beans	317	Intercept	3.20	0.39					0.45
			Pre-Bt years (1976-1995)	-0.02	0.01	2.68	1	305.3	0.101	0.008
			Bt years (1996-2016)	-0.12	0.01	164.96	1	305.6	<0.0001	0.33
	Sweet corn	317	Intercept	2.09	0.34					0.34
			Pre-Bt years (1976-1995)	-0.01	0.01	2.47	1	305.3	0.117	0.007
			Bt years (1996-2016)	-0.08	0.01	97.93	1	305.7	<0.0001	0.23
Helicoverpa zea	Sweet corn	294	Intercept	6.40	0.55					0.23
			Pre-Bt years (1976-1995)	0.11	0.02	43.68	1	46.3	<0.0001	0.17
			Bt years (1996-2016)	-0.11	0.02	53.86	1	65.0	<0.0001	0.22
Number of recommended insecticidal sprays as a function of national average Bt corn										
Ostrinia nubilalis	Peppers	179	Intercept	5.25	0.75					
			Bt corn (%)	-0.05	0.01	76.04	1	168.9	<0.0001	0.49
	Green beans	179	Intercept	3.09	0.37					
			Bt corn (%)	-0.03	0.00	118.9	1	168.8	<0.0001	0.41
	Sweet corn	179	Intercept	2.01	0.29					
			Bt corn (%)	-0.02	0.00	74.55	1	168.9	<0.0001	0.47
Helicoverpa zea	Sweet corn	172	Intercept	6.17	0.50					
			Bt corn (%)	-0.02	0.00	40.11	1	162.2	<0.0001	0.20
Number of recommended insecticidal sprays as a function of Bt corn adoption in crop-reporting district										
Ostrinia nubilalis	Peppers	26	Intercept	5.04	0.95					
			Bt corn (%)	-0.04	0.01	14.12	1	16.8	0.002	0.46
		26	Intercept	2.74	0.45					

	Green beans		Bt corn (%)	-0.02	0.01	22.02	1	16.1	<0.001	0.58
	Sweet corn	26	Intercept	1.92	0.36					
			Bt corn (%)	-0.02	0	13.87	1	16.8	0.002	0.45
Helicoverpa zea	Sweet corn	26	Intercept	6.07	0.65					
			Bt corn (%)	-0.02	0.01	8.161	1	16.0	0.011	0.34

Table S4. Source literature for pesticide efficacy trials evaluating *Ostrinia nubilalis* damage in untreated, control plots of mid-Atlantic peppers and sweet corn.

Year	Sweet corn	Peppers
1983	(14)	
1985	(15, 16)	
1986	(17)	(18, 19)
1987	(20)	
1988	(21–23)	
1989	(24)	
1990	(25, 26)	
1991	(27)	
1992	(28)	
1993	(29–31)	
1998	(32, 33)	
2000	(34)	
2001		(35, 36)
2002	(36, 37)	
2003		(38)
2005	(39)	
2006	(40)	(41)
2007		(42)
2008		(42, 43)
2009	(44)	

Tables S5-S8. Summary results for model selection relating Bt adoption and environmental factors to moth captures. Candidate models were ranked based on based on Akaike Information Criteria corrected for small sample sizes (AICc) and the best model selected based on Likelihood ratio test between top two models.

Table S5. Rank of models analyzing interactive and individual effects of national Bt adoption % (bt), avg. temperature (temp) and avg. precipitation (rain) on yearly captures of *Ostrinia nubilalis* during 1996-2016.

	(Intercept)	bt	prec	temp	bt: rain	bt: temp	rain: temp	bt: rain: temp	df	logLik	AICc	delta	weight
6	-6.21	-0.042	-	0.404	-	-	-	-	5	-188.81	387.97	0.00	0.936
8	-4.58	-0.042	-0.004	0.356	-	-	-	-	6	-190.45	393.39	5.42	0.062
22	-5.76	-0.054	-	0.381	-	0.001	-	-	6	-194.19	400.87	12.90	0.001
24	-4.03	-0.056	-0.004	0.328	-	0.001	-	-	7	-195.82	406.29	18.32	0.000
40	-6.48	-0.042	0.008	0.453	-	-	-0.001	-	7	-196.18	407.02	19.05	0.000
16	-4.43	-0.048	-0.006	0.360	0.000	-	-	-	7	-199.02	412.69	24.72	0.000
56	-5.91	-0.054	0.008	0.424	-	0.001	-0.001	-	8	-201.56	419.96	31.99	0.000
4	2.55	-0.036	-0.006	-	-	-	-	-	5	-204.83	420.02	32.05	0.000
2	1.52	-0.036	-	-	-	-	-	-	4	-206.59	421.40	33.43	0.000
32	-3.77	-0.065	-0.006	0.327	0.000	0.001	-	-	8	-204.35	425.54	37.57	0.000
48	-7.12	-0.051	0.012	0.502	0.000	-	-0.001	-	8	-204.53	425.91	37.94	0.000
64	-6.46	-0.067	0.012	0.469	0.000	0.001	-0.001	-	9	-209.87	438.80	50.83	0.000
12	2.64	-0.038	-0.007	-	0.000	-	-	-	6	-213.45	439.39	51.42	0.000
128	-1.95	-0.208	-0.017	0.236	0.001	0.008	0.001	0.000	10	-218.44	458.19	70.22	0.000
1	0.13	-	-	-	-	-	-	-	3	-275.70	557.54	169.58	0.000
5	0.63	-	-	-0.025	-	-	-	-	4	-277.20	562.63	174.67	0.000
3	1.16	-	-0.006	-	-	-	-	-	4	-277.73	563.69	175.72	0.000
7	2.91	-	-0.007	-0.086	-	-	-	-	5	-279.00	568.35	180.38	0.000
39	-4.53	-	0.043	0.294	-	-	-0.003	-	6	-283.45	579.38	191.41	0.000

Likelihood ratio test among top two models and fixed effects in final model selected (in bold)

fixed effects	Df	AIC	BIC	logLik	deviance	Chisq	Chi DF	Pr(>Chisq)
temp + bt + rain	**6**	**364.230**	**383.350**	**-176.120**	**352.230**	**8.165**	**1**	**0.00427**
bt + temp	5	370.390	386.330	-180.200	360.390			

Table S6. Rank of models analyzing interactive and individual effects of Bt adoption % in crop-reporting district (bt), avg. temperature (temp) and avg. precipitation (rain) on yearly captures of *Ostrinia nubilalis* during 2002-2013.

	(Intercept)	bt	rain	temp	bt: rain	bt: temp	rain: temp	bt: rain: temp	df	logLik	AICc	delta	weight
2	1.24	-0.029	-	-	-	-	-	-	4	-26.61	63.13	0.00	0.676
6	-5.12	-0.031	-	0.332	-	-	-	-	5	-25.86	64.71	1.58	0.307
1	-0.08	-	-	-	-	-	-	-	3	-32.26	71.61	8.48	0.010
8	-7.82	-0.028	0.008	0.381	-	-	-	-	6	-28.60	73.61	10.48	0.004
4	0.41	-0.027	0.004	-	-	-	-	-	5	-30.77	74.53	11.40	0.002
5	-1.85	-	-	0.091	-	-	-	-	4	-33.09	76.08	12.95	0.001
22	-6.72	0.028	-	0.415	-	-0.003	-	-	6	-30.22	76.87	13.74	0.001
3	-2.84	-	0.015	-	-	-	-	-	4	-33.88	77.66	14.53	0.000
7	-5.56	-	0.015	0.131	-	-	-	-	5	-34.49	81.98	18.85	0.000
24	-9.83	0.039	0.008	0.488	-	-0.003	-	-	7	-32.90	86.03	22.90	0.000
40	-9.62	-0.028	0.017	0.474	-	-	0.000	-	7	-33.47	87.16	24.03	0.000
12	-0.73	0.027	0.011	-	0.000	-	-	-	6	-37.17	90.77	27.64	0.000
16	-8.70	0.012	0.013	0.384	0.000	-	-	-	7	-35.69	91.60	28.47	0.000
39	2.97	-	-0.028	-0.321	-	-	0.002	-	6	-38.77	93.95	30.82	0.000
56	-17.85	0.061	0.046	0.918	-	-0.005	-0.002	-	8	-37.56	99.58	36.45	0.000
48	6.30	0.060	-0.064	-0.479	0.000	-	0.005	-	8	-39.73	103.92	40.79	0.000
32	-10.99	0.091	0.014	0.499	0.000	-0.004	-	-	8	-39.85	104.17	41.04	0.000
64	-0.41	0.088	-0.036	-0.103	0.000	-0.002	0.003	-	9	-44.06	117.36	54.23	0.000
128	6.12	-0.523	-0.075	-0.444	0.003	0.029	0.005	0.000	10	-51.31	137.29	74.16	0.000

Likelihood ratio test among top two models and fixed effects in final model selected (in bold)

fixed effects	Df	AIC	BIC	logLik	deviance	Chisq	Chi Df	Pr(>Chisq)
bt + temp	**5**	**47.901**	**54.191**	**-18.951**	**37.901**	**4.5805**	**1**	**0.03234**
bt	4	50.482	55.514	-21.241	42.482			

Table S7. Rank of models analyzing interactive and individual effects of national Bt adoption % (bt), avg. temperature (temp) and avg. precipitation (rain) on yearly captures of *Helicoverpa zea* during 1996-2016.

	(Intercept)	bt	rain	temp	bt: rain	bt: temp	rain: temp	bt: rain: temp	df	logLik	AICc	delta	weight
6	-8.42	-0.029	-	0.514	-	-	-	-	5	-189.39	389.14	0.00	0.996
22	-9.52	0.000	-	0.571	-	-0.001	-	-	6	-194.41	401.32	12.19	0.002
8	-8.40	-0.029	0.000	0.514	-	-	-	-	6	-194.86	402.24	13.10	0.001
40	-15.06	-0.029	0.042	0.852	-	-	-0.002	-	7	-199.11	412.90	23.76	0.000
24	-9.51	0.000	0.000	0.570	-	-0.001	-	-	7	-199.88	414.45	25.31	0.000
16	-9.26	-0.005	0.005	0.512	0.000	-	-	-	7	-201.43	417.53	28.40	0.000
56	-16.29	0.002	0.042	0.915	-	-0.002	-0.002	-	8	-204.10	425.09	35.95	0.000
32	-10.78	0.035	0.006	0.587	0.000	-0.002	-	-	8	-206.25	429.38	40.24	0.000
48	-13.84	-0.009	0.034	0.754	0.000	-	-0.002	-	8	-206.46	429.80	40.66	0.000
2	1.48	-0.022	-	-	-	-	-	-	4	-214.05	436.35	47.21	0.000
64	-15.27	0.030	0.034	0.824	0.000	-0.002	-0.002	-	9	-211.30	441.71	52.57	0.000
4	1.92	-0.022	-0.003	-	-	-	-	-	5	-218.36	447.08	57.94	0.000
128	-6.32	-0.253	-0.022	0.361	0.002	0.012	0.001	0.000	10	-218.90	459.17	70.03	0.000
12	0.87	0.006	0.004	-	0.000	-	-	-	6	-224.47	461.45	72.31	0.000
5	-5.15	-	-	0.290	-	-	-	-	4	-236.30	480.83	91.69	0.000
1	0.59	-	-	-	-	-	-	-	3	-238.12	482.39	93.25	0.000
7	-4.71	-	-0.001	0.279	-	-	-	-	5	-241.31	492.98	103.84	0.000
3	1.00	-	-0.002	-	-	-	-	-	4	-242.68	493.60	104.46	0.000
39	-14.81	-	0.066	0.794	-	-	-0.003	-	6	-244.55	501.61	112.47	0.000

Likelihood ratio test among top two models and fixed effects in final parsimonious model selected (in bold)

fixed effects	Df	AIC	BIC	logLik	deviance	Chisq	Chi Df	Pr(>Chisq)
bt + temp	**5**	**370.06**	**385.8**	**-180.03**	**360.06**	**0.5434**	**1**	**0.461**
bt + temp + bt : temp	6	371.52	390.4	-179.76	359.52			

Table S8. Rank of models analyzing interactive and individual effects of Bt adoption % in crop-reporting district (bt), avg. temperature (temp) and avg. precipitation (rain) on yearly captures of *Helicoverpa zea* during 2002-2013.

	(Intercept)	btperc	rain	temp	btperc: rain	btperc: temp	rain: temp	btperc: rain: temp	df	logLik	AICc	delta	weight
6	-11.80	-0.030	-	0.699	-	-	-	-	5	-24.79	62.58	0.00	0.993
8	-11.15	-0.031	-0.004	0.705	-	-	-	-	6	-28.99	74.40	11.82	0.003
5	-6.82	-	-	0.373	-	-	-	-	4	-32.65	75.21	12.62	0.002
22	-12.16	-0.019	-	0.718	-	-0.001	-	-	6	-29.51	75.45	12.87	0.002
1	0.46	-	-	-	-	-	-	-	3	-34.79	76.67	14.09	0.001
2	1.39	-0.020	-	-	-	-	-	-	4	-35.40	80.70	18.12	0.000
40	-36.06	-0.034	0.123	2.053	-	-	-0.007	-	7	-31.08	82.39	19.81	0.000
7	-7.70	-	0.004	0.382	-	-	-	-	5	-36.57	86.13	23.55	0.000
3	0.26	-	0.001	-	-	-	-	-	4	-38.74	87.39	24.81	0.000
24	-11.02	-0.036	-0.004	0.700	-	0.000	-	-	7	-33.70	87.62	25.04	0.000
4	3.50	-0.025	-0.010	-	-	-	-	-	5	-38.39	89.78	27.20	0.000
16	-13.98	0.035	0.005	0.774	0.000	-	-	-	7	-35.15	90.51	27.93	0.000
56	-40.66	0.018	0.138	2.290	-	-0.003	-0.008	-	8	-35.55	95.57	32.99	0.000
39	-18.79	-	0.061	0.971	-	-	-0.003	-	6	-40.71	97.84	35.26	0.000
48	-35.11	-0.029	0.118	1.994	0.000	-	-0.007	-	8	-38.43	101.32	38.74	0.000
32	-12.32	-0.019	0.005	0.690	0.000	0.003	-	-	8	-39.62	103.72	41.14	0.000
12	2.06	0.043	-0.002	-	0.000	-	-	-	6	-44.77	105.95	43.37	0.000
64	-49.93	0.011	0.182	2.828	0.000	-0.004	-0.010	-	9	-42.61	114.46	51.88	0.000
128	-22.84	-1.476	0.038	1.365	0.008	0.073	-0.002	0.000	10	-46.88	128.42	65.84	0.000

Likelihood ratio test among top two models and fixed effects in final parsimonious model selected (in bold)

fixed effects	Df	AIC	BIC	logLik	deviance	Chisq	Chi Df	Pr(>Chisq)
temp + bt	**5**	**44.766**	**51.056**	**-17.383**	**34.766**	**0.6**	**1**	**0.4386**
bt + temp + rain	6	46.166	53.714	-17.083	34.166			

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