A Structural Model of US Corn Farmers' Pest Control Decisions: Rootworm Resistance in US Corn Fields

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INTRODUCTION

Monsanto introduced genetically engineered, rootworm-resistant (Bt-CRW) seeds in 2003. Unfortunately, it appears that rootworms may be adapting to the toxins produced by these seeds:

- 2009: Unexpectedly high yield losses were first reported in Illinois and Iowa.
- 2011: Reports of unexpectedly high yield losses spread to MN, NE, and SD.
- 2012: Entomologists published a public letter suggesting that EPA act with "a sense of urgency" to prevent resistance from developing.
- 2015: The EPA proposes a bolstered framework for rootworm-resistance management.

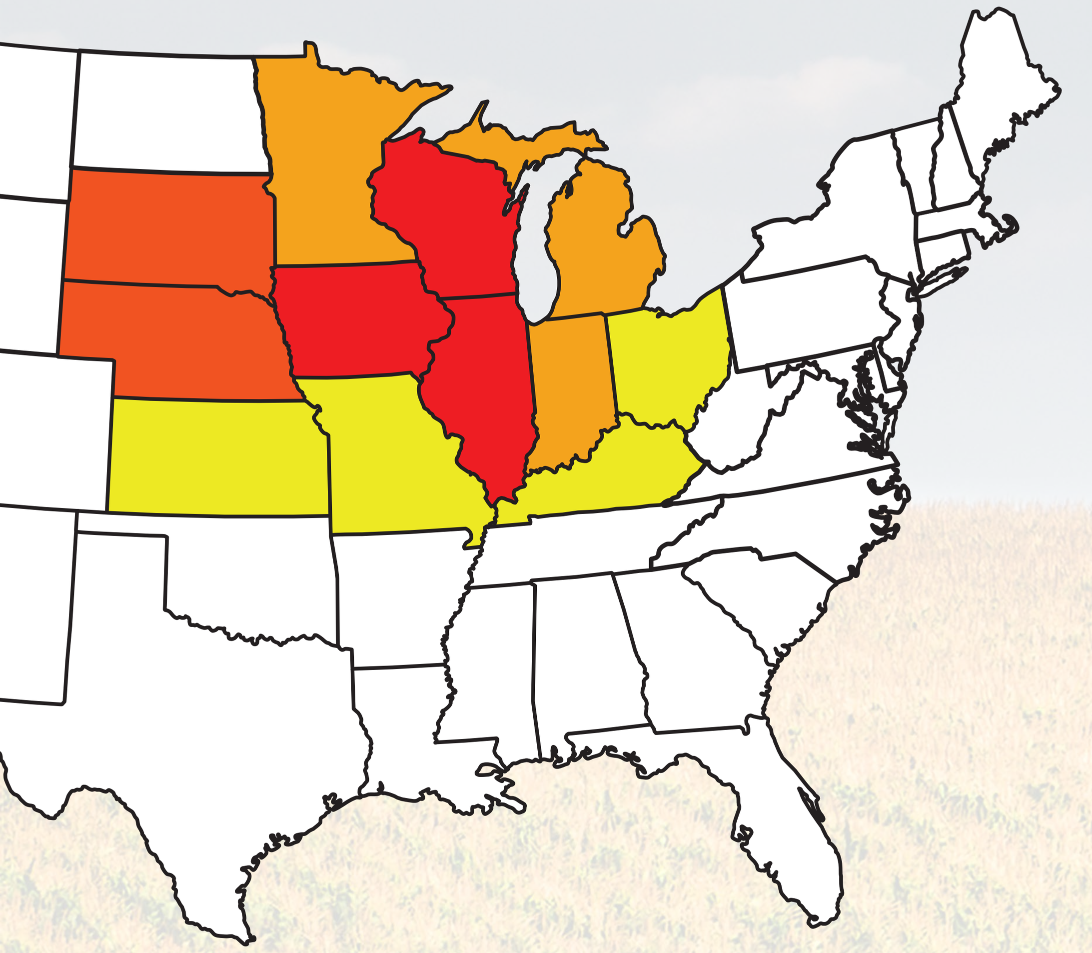
RESEARCH QUESTIONS

1. How does Bt-CRW adoption affect yields/insecticide use?
2. Have the benefits associated with Bt-CRW adoption changed over time? Can these changes be attributed to the development of rootworm resistance?

Average expected yield losses from rootworms (on untreated acres)

Bushels / Acre

5-7.5 | 7.5-10 | 10-12.5 | 12.5-17.5



Source: ARMS Phase II Corn Surveys (2005 and 2010).

REFERENCES

Lichtenberg, E., and D. Zilberman. 1986. "The Economics of Damage Control: Why Specification Matters." *American Journal of Agricultural Economics 68: 261-273.*

Wooldridge, J. 2014. "Quasi-maximum likelihood estimation and testing for nonlinear models with endogenous explanatory variables." *Journal of Econometrics 182: 226-234.*

THE TIMING OF CORN FARMERS' INSECTICIDE USE DECISIONS

(Farmers observe environmental conditions)

FORMULATING A DAMAGE ABATEMENT MODEL OF PEST CONTROL DECISIONS

Damage abatement models account for the fact that pesticides increase yields if (and only if) pests are present (Lichtenberg and Zilberman, 1986). Production is modeled such that $Y=HG$, where H represents potential yields and $G\in[0,1]$ represents abatement (the percentage of output not damaged by pest infestations).

- In this study, abatement is characterized using a Gumbel distribution:

$$Y=HG_{CRW}G_{CRB}\exp(\varepsilon) \quad \text{s.t.}$$
$$G_{CRB}=\exp(-Z_{CRB}\exp(-a-bBt_{CRB}-cIns_T))$$
$$G_{CRW}=\exp(-Z_{CRW}\exp(-d-eBt_{CRW}-fIns_S))$$

where, Y represents yields, $\mathcal{H}$ represents potential output, G represents abatement, Z represents pest pressure, Bt is an indicator for insect resistant seed use, Ins_T represents topical insecticide use, Ins_S represents soil insecticide use, CRB is an abbreviation for corn borers, CRW is an abbreviation for corn rootworms, $\{a,b,c,d,e,f\}$ are parameters, and ε is an error term.

- Estimating an empirical model of $Y=HG_{CRW}G_{CRB}\exp(\varepsilon)$ is complicated by the endogeneity of input use decisions. Because the production function is multiplicatively separable, and because insecticide use decisions are made sequentially, it is possible to estimate the parameters of G_{CRW} by deriving and estimating a demand function for soil insecticides.

SOLVING THE STRUCTURAL MODEL

The theoretical model is solved recursively:

Stage 2: Deriving a Demand Function for Topical Insecticides

First, a demand function for topical insecticides is derived by solving the second stage of the farmers' profit maximization problem:

$$\max_{Ins_T} \quad \pi \equiv pY - p_T Ins_T = pHG_{CRW}\exp\left(\exp\left(-a-bBt_{CRB}-cIns_T+Z_{CRB}\right)\right)-p_T Ins_T$$
$$\text{s.t.} \quad Z_{CRB}=\exp\left(z_{CRB}'\beta_{z_{CRB}}\right)$$
$$\Rightarrow Ins_T^* = \frac{1}{c}\left[z_{CRB}'\beta_{z_{CRB}} + \ln\left(-W\left(-\frac{p_T}{cPHG_{CRW}\exp(v)]}\right)^{-1}\right) - a - bBt_{CRB}\right]$$

(where z_{CRB} is a vector of factors affecting the severity of corn borer infestations, P represents corn prices, p_T represents topical insecticide prices, W is the product log function, and v is a realization of ε)

Stage 1: Deriving a Demand Function for Soil Insecticides

Next, a demand function for soil insecticides is derived by substituting Ins_T^* into the first stage of the model and solving it:

$$\max_{Ins_S, Bt_{CRB}, Bt_{CRW}} \quad \mathrm{E}[\pi] \equiv P\mathrm{E}[\mathrm{Y}] - p_S Ins_S - p_T \mathrm{E}\left[Ins_T^*\right] - p_{CRW}Bt_{CRW} - p_{CRB}Bt_{CB}$$
$$\text{s.t.} \quad Z_{CRW}=\exp\left(z_{CRW}'\beta_{z_{CRW}}\right)$$
$$\Rightarrow Ins_S^* = \frac{1}{f}\left[Z_{CRW}'\beta_{Z_{CRW}} + \ln\left(\frac{fP\mathrm{E}[\mathrm{Y}]}{p_s}\right) - d - eBt_{CRW}\right]$$

(where p_S represents soil insecticide prices, p_{CRW} represents the price of Bt-CRW seeds, and p_{CRB} represents the price of Bt-CRB seeds, and z_{CRW} is a vector of factors affecting the severity of rootworm infestations)

ESTIMATING SOIL INSECTICIDE DEMAND

A two-stage, control function-based approach is used to account for the endogeneity of seed choices and expected yields:

Step 1: Estimating Control Functions for Bt-CRW Adoption/Expected Yields

- A reduced-form probit model is used to analyze farmers' Bt-CRW adoption decisions. A reduced-form, linear specification is used to analyze expected yields.
- Residuals (denoted $R_{Bt_{CRW}}$ and $R_{\mathrm{E}[Y]}$) are calculated using the reduced form regression results and used as control functions in Step 2.

Step 2: Estimating an Extreme Value Distributed, Left-Censored, Soil Insecticide Demand Function

A censored, soil insecticide demand function is estimated using maximum likelihood:

- Likelihood ratio tests suggest that the data is Gumbel (rather than Frechet or Weibull) distributed. Therefore, the likelihood function used to estimate the model is:

$$\mathcal{L}=\prod_{i=1}^{N}\left[\frac{1}{B}\exp\left(\frac{Ins_s-\widehat{Ins_s}}{B}-\gamma-\exp\left(\frac{Ins_s-\widehat{Ins_s}}{B}-\gamma\right)\right)^{I_i(Ins_s)}\exp\left(-\exp\left(\frac{\widehat{Ins_s}}{B}-\gamma\right)\right)^{1-I_i(Ins_s)}\right]$$

$$\text{s.t.} \quad \widehat{Ins_s}=\text{cons}+\frac{1}{f}\left[Z_{CRW}'\beta_{Z_{CRW}}+\ln\left(\frac{fP\mathrm{E}[Y]}{p_s}\right)-Bt_{CRW}\left(e+e_{10}Ind_{10}+e_{10,Btl}Bt_{CRW,lag}Ind_{10}\right)+\beta_{Bt}R_{Bt_{CRW}}+\beta_{\mathrm{E}[Y]}R_{\mathrm{E}[Y]}\right]$$

where γ is Euler's constant, $I_i(Ins_s)$ indicates whether soil insecticide use is positive, Ind_{10} is an indicator for 2010, and $Bt_{CRW,cc}$ is an indicator for consecutive Bt-CRW seed use.

- $\hat{e}_{10}$ tests whether the effectiveness of Bt-CRW seeds changed from 2005 to 2010.
- $\hat{e}_{10,Btl}$ tests whether planting Bt-CRW seeds in consecutive rotations induced resistance to develop over the course of the study period.
- Each observation's contribution to the likelihood function is scaled using NASS generated weights.
- Jackknifed standard errors are used to account for the two-stage nature of the empirical approach.

DATA

Descriptive Statistics	Bt-CRW Users		Non-Bt-CRW Seed Users	
	2005	2010	2005	2010
Yield Goals[1]	166.81	176.54	158.88	161.15
Unadjusted Soil (CRW) Insecticide Use[2]	0.01	0.01	0.05	0.01
Soil Insecticide Use (in lbs of Chlorpyrifos)[2]	0.09	0.06	0.25	0.05
Incidence of Soil Insecticide Use	9.1%	8.6%	21%	5%
Expected Yield Losses from Rootworms[3]	13.70	13.14	11.69	9.15
Deviation from Average February Precipitation[4]	-5.98	6.09	-2.61	7.85
Rock Fragment Content[5]	5.63	7.07	7.51	9.06
Soil Ph	6.58	6.36	6.23	6.17
Number of Consecutive Corn Rotations	0.56	0.67	0.44	0.42
Number of Observations	128	729	1085	705

[1] in bushels/acre.
[2] in pounds of active ingredient/planted acre.
[3] on untreated acres.
[4] in inches.
[5] percent of soil weight.

- The ARMS Phase II Corn Survey is the primary source of data used in the study.
- The dataset contains 2,647 field-level observations for farms located in IL, IN, IA, KS, KY, MI, MN, MO, NE, OH, SD, and WI.
- While approximately 20 percent of corn farmers applied soil insecticides in 2005, only 7 percent applied soil insecticides in 2010.
- Insecticides have different potencies. Therefore, each application is converted into an equivalent dosage of Lorsban 15.

REGRESSION RESULTS

Reduced Form Models of Bt-CRW Adoption and Expected Yield	Yield Goal (OLS)	Bt-CRW Seed Use (Probit)
ln(Average State Level Premiums For Bt-CRW Seeds)	-0.04	-0.48
Soil Insecticide Prices	-0.63	-0.14 ***
Corn Price	-2.03	1.05 *
ln(Farm Size)[1]	4.55 ***	0.14 ***
Consecutive Corn Rotations	1.29 **	0.14 ***
Av. State Level Expected Yield Losses (from Rootworms)	1.32	0.44 ***
NCRS Soil Productivity Index	43.78 ***	-0.82 ***
Indicator for Erodible Soils	-5.56 **	-0.14
Soil Ph	12.73 ***	0.37 ***
Deviation from Average Winter Temperature	-0.18	0.006
Deviation from Average February Precipitation	0.20 ***	-0.005
Rock Fragment Content	0.006	-0.04 ***
Indicator for 2010	13.50	-1.39
Constant	45.29 **	-3.88 ***
State Fixed-Effects	Yes	Yes
Pseudo R2/Adj R2	0.3071	0.3069
Number of Observations	2647	2647
Average Residual	**0.82**	**.0006[2]**

[1] Total corn acres planted on this operation.
[2] The generalized residual is calculated for the Probit model.

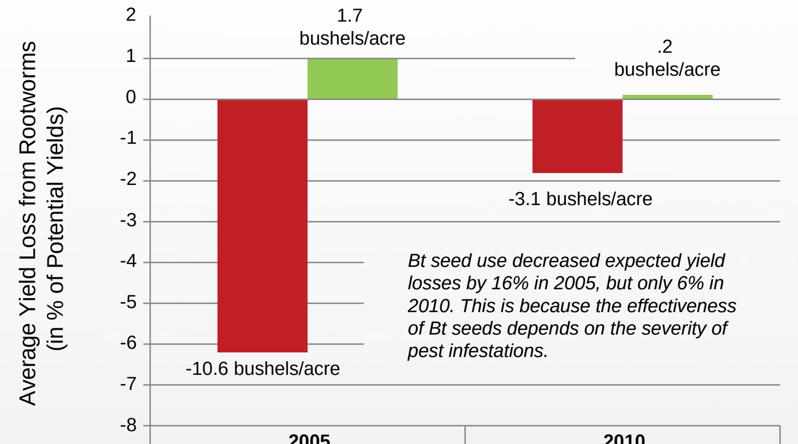
- Instruments for expected yields include: the presence of erodible soils and deviations from average February precipitation rates.
- Instruments for Bt-CRW adoption decisions include: input and output prices, average expected yield losses from rootworms, and the volume of rock fragments in the soil strata.

Structural Model of Soil Insecticide Demand		
Parameters of the Rootworm Abatement Function		
e	Bt-CRW Adoption	1.88 **
e_{10}	Interaction of Bt and 2010	-0.50 *
$e_{10,CC}$	Interaction of Bt, 2010, and Lagged Bt-CRW	-0.03
$-d/f$	Constant	-22.61 ***
f	Soil Insecticides	0.31 ***
Z_{Yl}	Av. State-Level Expected Yield Losses (from Rootworms)	0.29 **
Z_{cc}	Consecutive Corn Rotations	0.12
Z_{Ph}	Average Soil Ph	0.56 **
Z_{Fs}	Farm Size	0.06
Z_{10}	Indicator for 2010	-0.69 **
Z_{Wi}	Indicator for Wisconsin	0.55 **
Z_{Ind}	Indicator for Indiana	0.59 **
Z_{Ill}	Indicator for Illinois	0.41 *
Z_{Mn}	Indicator for Minnesota	0.30
Parameters of the Gumbel Distribution		
Standard Deviation		1.26 ***
Control Functions		
β_{Bt}	Generalized Residuals, Bt Adoption	0.78 **
$\beta_{E[Y]}$	Residuals of the Expected Yield Function	-0.004 **
Pseudo R2		**0.23**
Observations		**2647**

- Both β_{Bt} and $\beta_{E[Y]}$ are significant. Therefore, seed choices and expected yields are endogenous.
- On average, the severity of pest infestations (Z_{10}) and the effectiveness of Bt seeds (e_{10}) decreased from 2005 to 2010.
- Though the effectiveness of Bt-CRW seeds decreased from 2005 to 2010, this phenomenon was not pronounced on farms where Bt-CRW seeds were planted in consecutive years ($e_{10,cc} \approx 0$). If resistance had developed, it should have been observable on farms where selective pressure was especially high.

IMPACTS OF BT-CRW ADOPTION

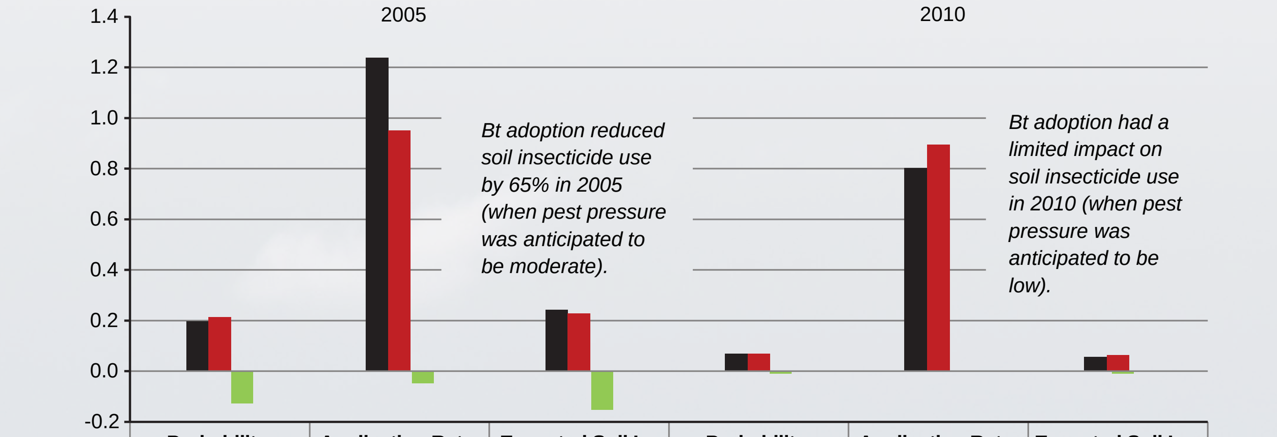
Rootworm-Resistant (Bt-CRW) Corn Reduces Yield Losses



	2005	2010
Predicted Yield Loss	-6.2%***	-1.8%***
Impact of Rootworm-Resistant Seed Use	0.95%***	0.11%***

On average, Bt-CRW adoption increased yields by approximately 1.7 bushels per acre in 2005 and .2 bushels per acre in 2010.

Rootworm-Resistant (Bt-CRW) Corn Decreases Soil Insecticide Use



	Probability of Soil Ins. Use, 2005	Application Rate, 2005 (lbs A.I. per Acre)	Expected Soil Ins. Use, 2005 (lbs A.I. per Acre)	Probability of Soil Ins. Use, 2010	Application Rate, 2010 (lbs A.I. per Acre)	Expected Soil Ins. Use, 2010 (lbs A.I. per Acre)
Sample Mean	19.6%***	1.24***	0.24***	7.0%***	0.80***	0.06***
Model Prediction	21.4%***	0.95***	0.23***	6.9%***	0.89***	0.06***
Impact of Rootworm-Resistant Seed Use	-12.6%***	-0.05***	-0.15***	-0.8%***	-0.001***	-0.01***

On average, using rootworm-resistant seeds decreased soil insecticide use by approximately 65% in 2005 and 10% in 2010. This decrease was driven by a reduction in the probability of usage (not a decrease in application rates).

Benefits of Adoption Tend To Be More Pronounced for Bt-CRW Adopters

		Abatement Level			Probability of Insecticide Use			Application Rate (Pounds Chlorpyrifos/Acre)[1]			Insecticide Use[1]		
		Model Prediction	Impact of Adoption (%)	Impact of Adoption (Bush/Acre)	Sample Mean	Model Prediction	Impact of Bt-CRW Adoption	Sample Mean	Model Prediction	Impact of Bt-CRW Adoption	Sample Mean	Model Prediction	Impact of Bt-CRW Adoption
Bt Adopters	2005	95.0%***	1.70%***	2.96***	8.4%	8.8%***	-19.8%***	1.14	0.90***	-0.07***	0.10	0.08***	-0.22***
	2010	98.2%***	0.09%***	0.15***	8.6%	8.3%***	-0.4%*	0.72	0.90***	-0.0002	0.06	0.08***	-0.003
Non-Adopters	2005	93.7%***	0.88%***	1.54***	20.8 %	22.7%***	-11.9%***	1.24	0.95***	-0.05***	0.26	0.24***	-0.14***
	2010	98.2%***	0.13%***	0.21***	5.1%	5.2%***	-1.1%***	0.96	0.89***	-0.003***	0.05	0.05***	-0.01***

[1]In Pounds of Active Ingredient per Planted Acre.

CONCLUSIONS

1. Rootworm resistance was not widespread as of 2010. Future work will analyze data that is being collected for 2013, 2014, 2015, and 2016.
2. Bt-CRW seed use reduced insecticide use from 2005 to 2010. For instance, farmers using Bt-CRW seeds would have tripled their soil insecticide use if they had planted conventional seeds in 2005.
3. Bt-CRW adoption increased U.S. corn yields over the course of the study period. The magnitude of the effect varied with the severity of the infestation.

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