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Has Resistance Taken Root? An Analysis of Bt Corn Seeds

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Introduction:

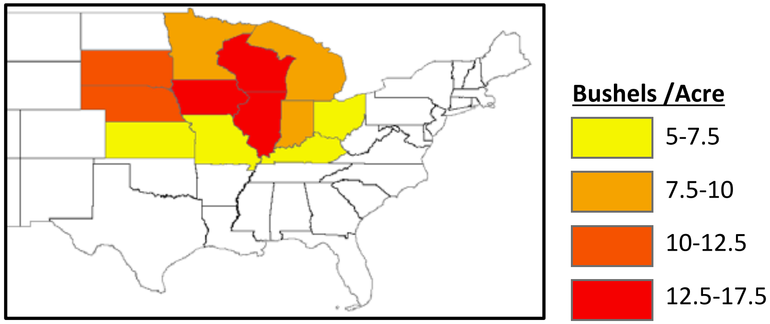
In 2003, Monsanto introduced genetically engineered, rootworm resistant (Bt-CRW) seeds. There is evidence that rootworms may be adapting to the toxins produced by these seeds:

- 2009: Unexpectedly severe crop damages were reported in Illinois and Iowa.
- 2011: Reports of crop damages spread to MN, NE, and SD.
- 2013: EPA concludes that resistance is not widespread, but acknowledges that resistance monitoring is beset by technical challenges.

Research Questions:

- How does Bt-CRW adoption affect yields/insecticide use?
- Has the effectiveness of Bt-CRW seeds changed over time? Can these changes be attributed to the development of rootworm resistance?

Expected Yield Losses from Corn Rootworms



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

Theoretical Model

- We assume that farmers are primarily interested in maximizing profits.
- We assume that insecticides and Bt seeds do not increase yields; they decrease damages from pest infestations.
- We assume that farmers are able to choose inputs, but not able to affect input or output prices.
- Given these assumptions we are able to use data that we observe (like prices, environmental conditions, and farmers input choices) to infer information about things that we would like to observe (like field level pest pressure, or the efficacy of Bt seeds), but do not.
- We are also able to come to some conclusions about how prices and environmental factors affect farmers' pest control decisions.

$$\max_{I, Bt \in \{0,1\}} \mathrm{E}[\pi] \text{ s.t.}$$
$$\pi = PY(I, Bt) - \mathrm{p}\, I - \mathrm{p}_{Bt}\, Bt$$
$$Y = \exp(-dR \exp(-aI - bBt))\Upsilon \exp(\varepsilon)$$

$$\Rightarrow \quad I^{*} = \frac{1}{a}\left[\ln(dR) + \ln\left(\frac{aP\mathrm{E}[\mathrm{Y}]}{p}\right) - bBt\right]$$

where R is the size of the rootworm population, Υ are undamaged crop yields, the parameters a and b reflect the efficacy of soil insecticides and Bt seeds, and the parameter d reflects the destructiveness of rootworm infestations.

Modeling Rootworm Damages and Control

- Famers can control 0% to 100% of rootworm infestations, and rootworms can damage 0% to 100% of yields. Therefore, we choose to specify the damage and control functions using exponential cumulative distribution functions:

  $$D = 1 - \exp\left(-dR\left(1 - C\left(I, Bt\right)\right)\right)$$

  $$C = 1 - \exp(-aI - bBt)$$

  where, d is a damage parameter, R(1-C(I,Bt)) is the size of the rootworm population following treatment, and a and b are pest control parameters.

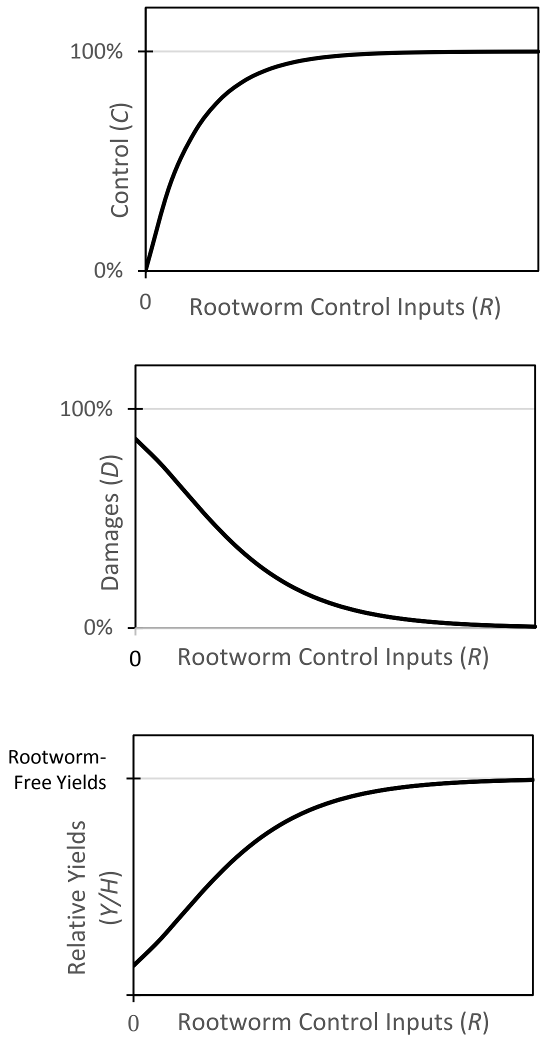
  This specification reflects the assumptions that rootworms (R) damage crops, that control (C) reduces damages, and that soil insecticide use and Bt-CRW seed use increase the percent of rootworms controlled ($\partial D/\partial R>0$, $\partial D/\partial C<0$, $\partial C/\partial I>0$, and $\partial C/\partial Bt>0$).

- Abatement, the percent of yields undamaged by rootworms, is defined as: G=1-D(R,C). Therefore, the specifications we've chosen for D and C imply that:

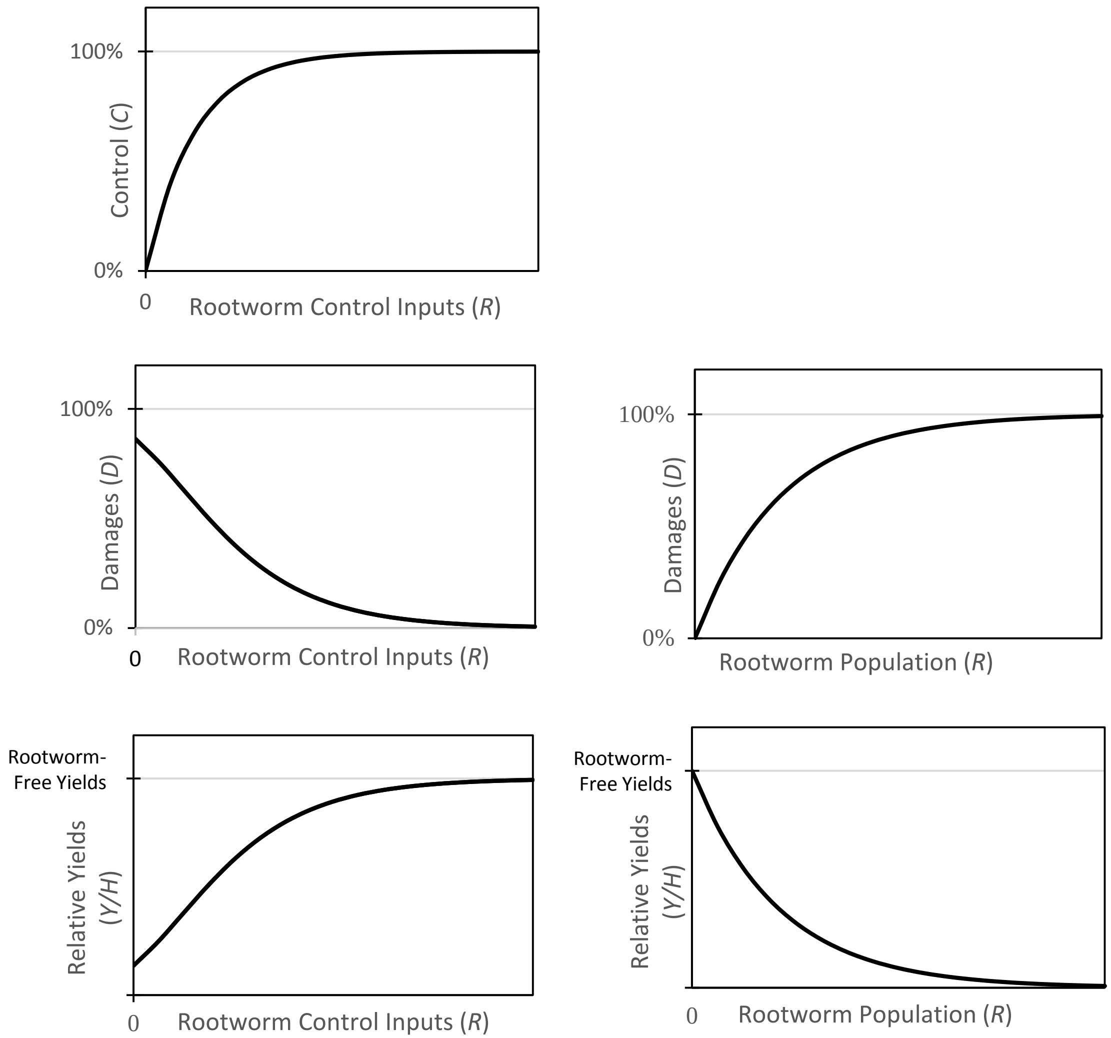
  $$G = \exp(-dR\exp(-aI - bBt))$$

- Notice that G is a type I generalized extreme value cumulative distribution function.

Modeling Rootworm Damages and Control



Modeling Rootworm Damages and Control



Kuhn Tucker Conditions

$$\max_{I,Bt\in\{0,1\}} \mathrm{E}[\pi] \text{ s.t.}$$

$$\pi = PY(I, Bt) - \mathrm{p}\, I - \mathrm{p}_{Bt}\, Bt$$

$$Y = \exp(-dR\exp(-aI - bBt))\Upsilon\exp(\varepsilon)$$

$$\Rightarrow$$

$$\frac{\partial \mathrm{E}[\pi]}{\partial I} = \mathrm{E}\left[P\frac{\partial Y}{\partial G}\frac{\partial G}{\partial I}\right] - p \le 0$$

$$= P\exp\left(-dR\exp\left(\text{-}aI \text{ -} bBt\right)\right)\Upsilon\,\mathrm{E}\left[\exp\left(\varepsilon\right)\right]dR\exp\left(\text{-}aI \text{ -} bBt\right)a - p \le 0$$

$$\frac{\partial \mathrm{E}[\pi]}{\partial I} I = 0$$

$$I \ge 0$$

Kuhn Tucker Conditions

The marginal benefit of insecticide use equals the marginal cost at:

$$I^{*} = \frac{1}{a}\left[\ln(dR) - \ln\left(-\mathrm{W}\left(\frac{-p}{aP\Upsilon\,\mathrm{E}\left[\exp(\varepsilon)\right]} \right)\right) - bBt \right],$$ where W is the product log function.

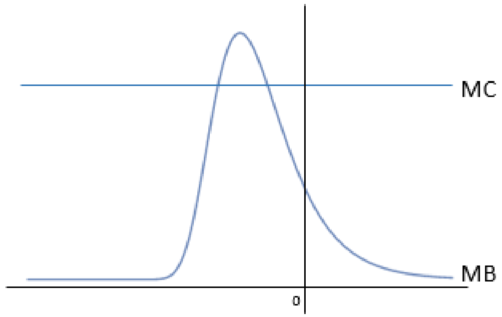
We find that the objective function is concave in the feasible region for the farmers in our sample. Therefore, the insecticide demand function is:

$$I = \max\left[0, \frac{1}{a}\left[\ln(dR) - \ln\left(-\mathrm{W}_0\left(\frac{-p}{aP\Upsilon\exp(\varepsilon)} \right)\right) - bBt \right]\right]$$

$$= \max\left[0, \frac{1}{a}\left[\ln(dR) + \ln\left(\frac{aP\mathrm{E}[\mathrm{Y}]}{p} \right) - bBt \right]\right]$$

Concavity of the Objective Function

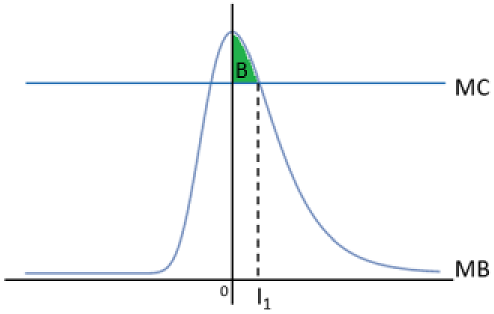
- Case (a) – Low Pest Pressure, Low Insecticide Price ⇒ Optimal *I=0*



Case (a) arises when the objective function is concave in the feasible region, but the marginal cost exceeds the marginal benefit. In this case, the total benefit of soil insecticide use is negative and decreasing in *I* for all *I*>0. Because using soil insecticides lowers profits, the argmax of the objective function at *I*=0.

Concavity of the Objective Function

- Case (b) – Medium Pest Pressure, Low Insecticide Price ⇒ Optimal $I=I_1$



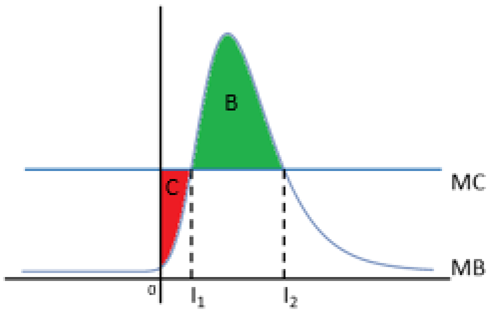
Case (b) arises when the objective function is concave in the feasible region (where $I>0$). In this case, there is an interior solution to the profit maximization problem: the point at which the marginal cost curve intersects the marginal benefit curve. The total benefit of soil insecticide use at I_1 is the area of region B.

In Wechsler and Smith (2018) we demonstrate that there is only one interior solution to the first order conditions in the feasible region. Thus, Cases (a) and (b) characterize our model solution.

In other words, the objective function is concave in the feasible region.

Concavity of the Objective Function

- Case (c) – High Pest Pressure, Low Insecticide Price ⇒ Optimal $I=I_2$

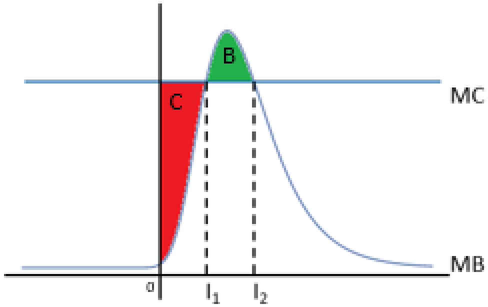


In case (c), the objective function is not concave in the feasible region. Therefore, identifying the global maximum entails comparing profits at $E[\pi|I=0]$, $E[\pi|I=I_1]$, and $E[\pi|I=I_2]$.

Using soil insecticides lowers profits for all $I<I_1$. Profits rise as insecticide use increases from I_1 to I_2, but fall thereafter. Crucially, the total benefit from insecticide use (the area of region B) is greater than the total cost of insecticide use (the area of region C). Therefore, the optimal level of insecticide use is positive.

Concavity of the Objective Function

- Case (d) – High Pest Pressure, High Insecticide Price ⇒ Optimal *I=0*



In case (d), the objective function is not concave in the feasible region. However, the total benefit of insecticide use (the area of region B) is smaller than the total cost (the area of region C). Consequently, the global max of the objective function is at I=0.

If case (d) characterizes the profit maximization problem then

$$I = \max\left[0, \frac{1}{a}\left[\ln(dR) + \ln\left(\frac{aP\mathrm{E}[\mathrm{Y}]}{p}\right) - bBt\right]\right]$$

is not the model solution.

Modeling the Efficacy of Bt-CRW Seeds

Resistance tends to develop on fields where Bt-CRW seeds have been planted in several consecutive seasons (Gassmann et al. 2011, 2012). However, the efficacy of Bt-CRW seeds (*b*) can also be affected by environmental factors (Wang et al. 2014). Therefore, we allow *b* to vary by year and rotation.

An indicator variable for the year 2010 (*T10*=1 if the year is 2010) accounts for widespread changes in environmental conditions between 2005 and 2010. An indicator for consecutive Bt-CRW seed use (*Btc*=1 if Bt-CRW seeds were planted in each of the two previous years) serves as a proxy for rootworm resistance.

Specifically, we let:

$$b = b_{05} + b_{10} T10 + b_{Btc} T10 \cdot Btc$$

Modeling Pest Pressure

We reparametrize pest pressure and restrict it to non-negative values such that:

$$dR = \exp\left(\alpha + \mathbf{X}'\boldsymbol{\beta} + \beta_{Cl}Cl + \beta_{Btc}Btc + m\right)$$

where α is a constant, ***X*** is a vector of variables reflecting farm and field-level conditions, *Cl* indicates lagged corn use (*Cl*=1 if corn was planted in the previous year), and *m* reflects error in our estimate of pest pressure (subsequently referred to as latent pest pressure).

The vector ***X*** includes variables such as a proxy for farm size, an indicator for 2010, and a proxy for farmers' perceptions about yield losses from rootworms.

We assume that contemporaneous choices affect rootworm control, that lagged choices affect rootworm pressure, and that *m* is observed by farmers but unobserved by the econometrician.

Quality Adjusting Soil Insecticide Use

Insecticide products have different potencies.

We account for these differences by assuming that all products have the same effectiveness at the label rate and letting $I \equiv q_k/L_k$, where q_k is the quantity of product k applied and L_k is the quantity of product k recommended by the manufacturer.

Empirical Approach

Given our assumptions about the efficacy of Bt seeds, pest pressure, and soil insecticide use, the interior solution of the model is:

$$I_i^* = \frac{1}{a}\left[\alpha + \mathbf{X}_i^{'}\boldsymbol{\beta} + \beta_{Cl} Cl_i + \beta_{Btc} Cl_i Btc_i + \ln\left(\frac{aP_i Yg_i}{p_i^f f_i}\right) - (b_{05} + b_{10} T10_i + b_{Btc} T10_i Btc_i) Bt_i\right] + \frac{m_i}{a}$$

where, *Yg* are yield goals (our proxy for expected yields), and p^f are insecticide prices per lineal foot and *f* are lineal feet per acre.

This equation can be reparametrized such that it is linear in parameters:

$$I_i^* = \beta_0 + \mathbf{X_i}\boldsymbol{\beta_x} + \beta_1 Cl_i + \beta_2 Cl_i Btc_i + \beta_3 \ln(P_i) + \beta_4 \ln(p_i^f) + \beta_5 \ln(f_i) + \beta_6 \ln(Yg_i)$$
$$+\beta_7 Bt_i + \beta_8 T10_i Bt_i + \beta_9 T10_i Btc_i Bt_i + \varepsilon_i$$

where, $\beta_0 = \frac{1}{a}\left[\alpha + \ln(a)\right]$, $\boldsymbol{\beta_x} = \frac{\boldsymbol{\beta}}{a}$, $\beta_1 = \frac{\beta_{Cl}}{a}$, $\beta_2 = \frac{\beta_{Btc}}{a}$, $\beta_3 = -\beta_4 = -\beta_5 = \beta_6 = \frac{1}{a}$, $\beta_7 = \frac{-b_{05}}{a}$, $\beta_8 = \frac{-b_{10}}{a}$, $\beta_9 = \frac{-b_{Btc}}{a}$, and $\varepsilon_i = \frac{m_i}{a}$.

Data

USDA

AGRICULTURAL RESOURCE MANAGEMENT SURVEY

CORN PRODUCTION PRACTICES AND COSTS REPORT

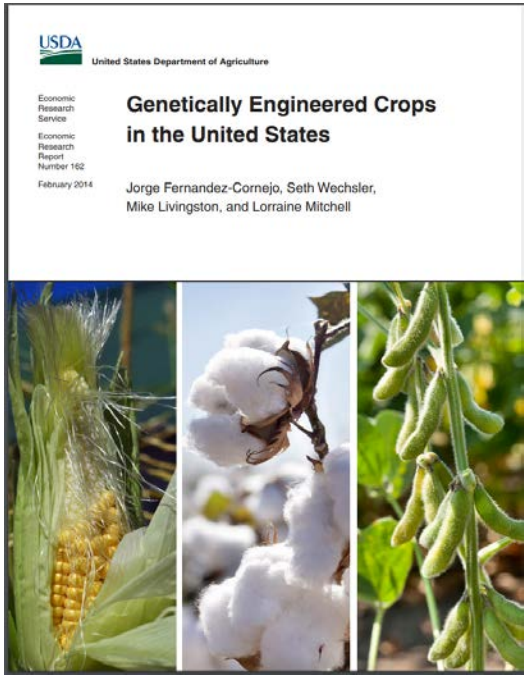
for 2010

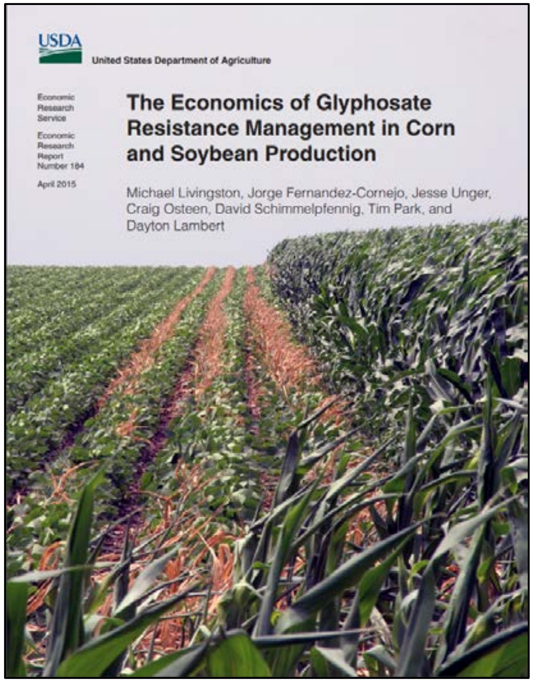
NATIONAL AGRICULTURAL STATISTICS SERVICE

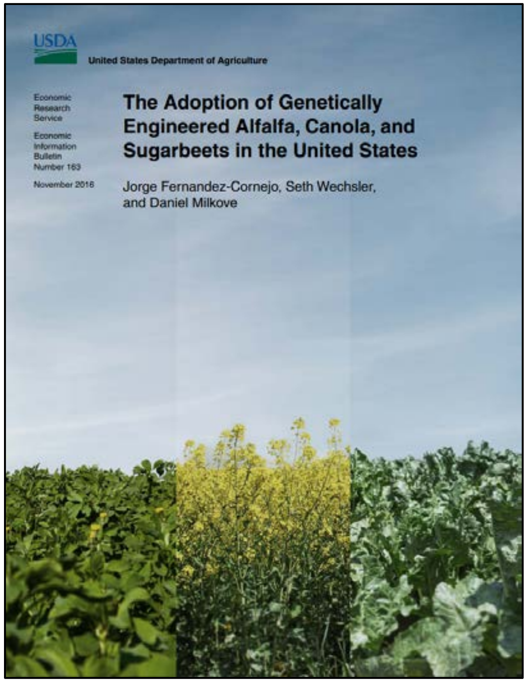
U.S. Department of Agriculture,
Rm 5030, South Building
1400 Independence Ave., S.W.
Washington, DC 20250-2000
Phone: 1-800-727-9540
Fax: 202-690-2090
Email: nass@nass.usda.gov

- The USDA ERS/NASS Agricultural Resource Management Survey (ARMS) is an annual, multiphase survey with a stratified, probability-weighted design.
- ARMS has three phases.
    - Phase 1 – A screening survey which is conducted during the summer; it is used to qualify farms for the other two survey phases.
    - Phase II - A survey that collects field-level, commodity-specific information about production practices; it is administered in the fall of the survey year.
    - Phase III – A survey that gathers operation level-information about households, farm finances and operator demographics.
- Producers of select field crops are administered approximately once every 5-9 years.
- The primary source of data used in this study is the ARMS Phase II Corn Data collected in 2005 and 2010.

ERS Uses ARMS Data To Produce a Wide Range of Publications, including:







Data

Primary Source:

Phase II of the Agricultural Resource Management Survey (ARMS), 2005 and 2010

Secondary Sources:

The NRCS's Soil Data and National Crop Commodity Datasets

Table 1. Average Select Farmer/Field Characteristics, by Year		
	2005	**2010**
Soil Insecticide Use (% of label rate)	0.13	0.06
Indicator for Soil Ins Use	0.14	0.07
Indicator for Bt-CRW Seed Use	0.10	0.56
Bt-CRW in Previous Year	0.03	0.13
Yield Goal (bushels per acre)	158	170
Expected Corn Price ($ per bushel)	2.52	3.89
Chlorpyrifos Price ($ per 1k lineal ft.)	0.82	0.77
Bt-CRW Price Premium ($ per bag)	16.75	33.35
Number of Observations	1167	1327

Source: Wechsler and Smith (2018)

- The dataset contains 2494 field-level observations for farms located in Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Missouri, Nebraska, Ohio, South Dakota, and Wisconsin.
- While approximately fourteen percent of corn farmers applied soil insecticides in 2005, only seven percent applied soil insecticides in 2010.
- While only ten percent used Bt-CRW seeds in 2005, approximately 56 percent used Bt-CRW seeds in 2010.
- Expected corn prices increased by over 50 percent from 2005 to 2010.
- 2010 was a relatively wet year. It is well known that the presence of wet or water-logged soils can reduce the severity of rootworm infestations.

ARMS Phase II Data about Pesticide Use, Seed Use, and Pest Pressure

- The ARMS Phase II Survey is a rich source of data about the quantity of every pesticide product applied, the mode of application, and its timing. This makes it possible to differentiate insecticides used to kill rootworms from insecticides used to kill other insects.
- The Phase II data also contains sufficient information to construct a two year history of seed choices and a five year history of crop rotations.
- Ideally, we would have access to field-level information about the severity of rootworm infestations. Unfortunately, we do not. However, the ARMS survey does ask farmers to estimate what yield losses would have been if rootworms had been untreated.

APPLICATIONS CODES for column 9	
1 Broadcast, ground without incorporation	6 Chisel/injected or knifed in
2 Broadcast, ground with incorporation	7 Banded in or over row
3 Broadcast, by aircraft	8 Foliar or directed spray
4 In seed furrow	9 Spot treatments
5 In irrigation water	

CHEMICAL PRODUCT NAME	LINE	2 What products were applied to this field? *[Show product codes from Respondent Booklet.]*	3 Was this product bought in liquid or dry form? *[Enter L or D]*	4 Was this part of a tank mix? *[If tank mix, enter line number of first product in mix.]*	5 When was this applied? 1 BEFORE planting 3 AT planting 4 AFTER Planting	6 OR How much was applied per acre per application?	7 What was the total amount applied per application in this field?	8 *[Enter unit code.]* 1 Pounds 12 Gallons 13 Quarts 14 Pints 15 Liquid Ounces 28 Dry Ounces 30 Grams	9 How was this product applied? *[Enter code from above.]*	10 How many acres in this field were treated with this product? ACRES	11 How many times was it applied? NUMBER	12 Were these applications made by--- 1 Operator, partner or family member? 2 Custom applicator? 3 Employee/Other?
	01	61		63	64	65 .__ __	73 .__ __	74	76	77 .__	79	80
	02	61		63	64	65 .__ __	73 .__ __	74	76	77 .__	79	80
	03	61		63	64	65 .__ __	73 .__ __	74	76	77 .__	79	80
	04	61		63	64	65 .__ __	73 .__ __	74	76	77 .__	79	80

Results

- Model 1 treats all explanatory variables as exogenous. Model 2 imposes parameter restrictions suggested by the theoretical model. Model 3 accounts for endogeneity.
- We find evidence that Bt-CRW seed use and yield goals are endogenous. The results suggest that pest pressure is systematically higher on fields where Bt-CRW seeds are planted and lower on fields where yield goals are high.
- Failing to account for endogeneity leads to underestimation of the effectiveness of Bt-CRW seeds.

Results of the Reduced Form Tobit Model

		(1)	(2)	(3)
Variables that Affect the Efficacy of Bt-CRW				
Bt-CRW	β_7	−0.83***	−0.83**	−4.06**
Bt-CRW*2010	β_8	0.78**	0.77*	1.23***
Bt-CRW*Bt-CRW lag*Corn lag lag*2010	β_9	−0.25	−0.28	−0.41
Variables that Affect Pest Pressure				
Constant	α	−13.26***	−9.79***	−16.08***
Expected Yield Loss	β_{X1}	1.23***	1.28***	1.23***
Soil pH	β_{X2}	0.07	0.03	0.39**
ln(Farm Size)	β_{X3}	0.33***	0.34***	0.42***
2010	β_{X4}	−2.12	−1.78***	−1.22
Corn lag	β_1	0.57***	0.56***	0.84***
Corn lag* Bt-CRW lag	β_2	−0.16	−0.12	0.11
Generalized Residual, Bt-CRW	m_{Bt}			1.71*
Residual, ln(Yield Goals)	m_{Y_g}			−1.56**
Residual, ln(Lineal Feet)	m_f			1.53
Other Variables				
ln(Corn Price)	β_3	2.40	1.48***	2.67***
ln(Yield Goal)	β_4	1.83***	1.48***	2.67***
ln(Chlorpyrifos Price)	β_5	−0.49	−1.48***	−2.67***
ln(Lineal Feet)	β_6	−1.15	−1.48***	−2.67***
Sigma	σ	1.30***	1.31***	1.29***
Number of Observations		2,494	2,494	2,494
Pseudo R^2		0.14	0.13	0.14

Source: Wechsler and Smith (2018)

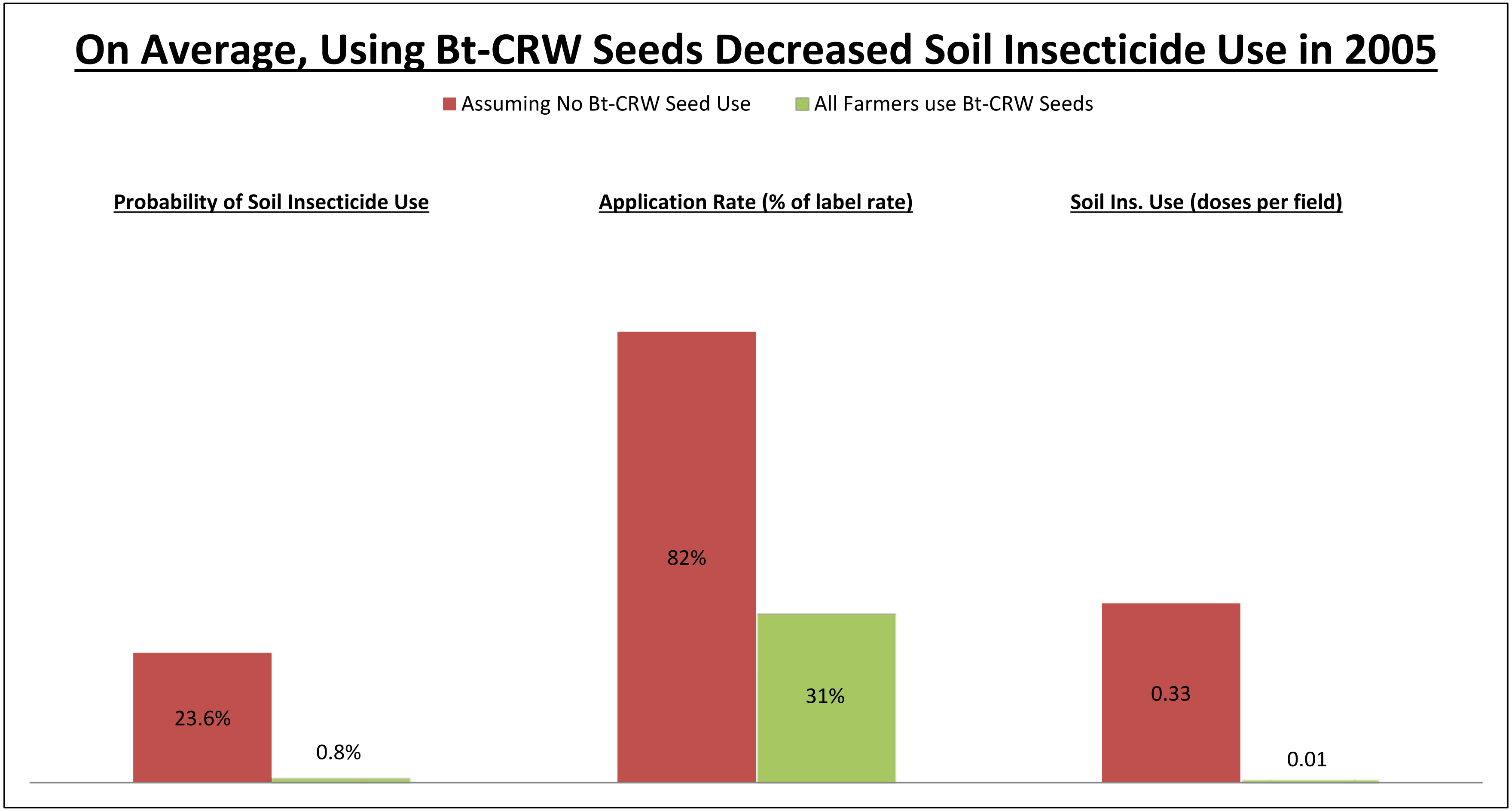
Results

Description	Expression	2005 No Bt	2005 With Bt	2005 M.E.	2010 No Bt	2010 With Bt	2010 M.E.
All Observations		(1,167 Observations)			(1,327 Observations)		
Yield (bushels per acre)	$E[Y \vert E[I]]$	157.25***	163.65***	6.40***	167.79***	171.13***	3.33***
Abatement (%)	$E[G \vert E[I]]$	94.61***	98.51***	3.90***	96.30***	98.26***	1.96***
Probability of Using Soil Insecticides (%)	$E[Pr(I^{*} > 0)]$	23.58***	0.84***	-22.74***	43.29***	5.17***	-38.11*
Application Rate (% of label rate)	$E[I \vert I^{*} > 0]$	81.93***	30.55***	-51.38***	107.62**	45.36***	-62.25
Soil Insecticide Use (% of label rate)	$E[I]$	32.54**	0.55**	-31.99**	67.04	3.54***	-63.50
Revenue (dollars per acre)	$P \cdot E[Y \vert E[I]]$	345.53***	359.59***	14. 06***	878.75***	896.20***	17.45***
Seed Cost (dollars per acre)	$E[p_{seed}] \cdot Seedrate$	40.23***	46.23***	6.00***	66.56***	79.40***	12.84***
Soil Insecticide Cost (dollars per acre)	$p \cdot E[I]$	4.45**	0.08**	-4.37***	8.57	0.43***	-8.13
Variable Profit (dollars per acre)	Revenue - Control Costs	-	-	12.45***	-	-	12.82

Source: Wechsler and Smith (2018)

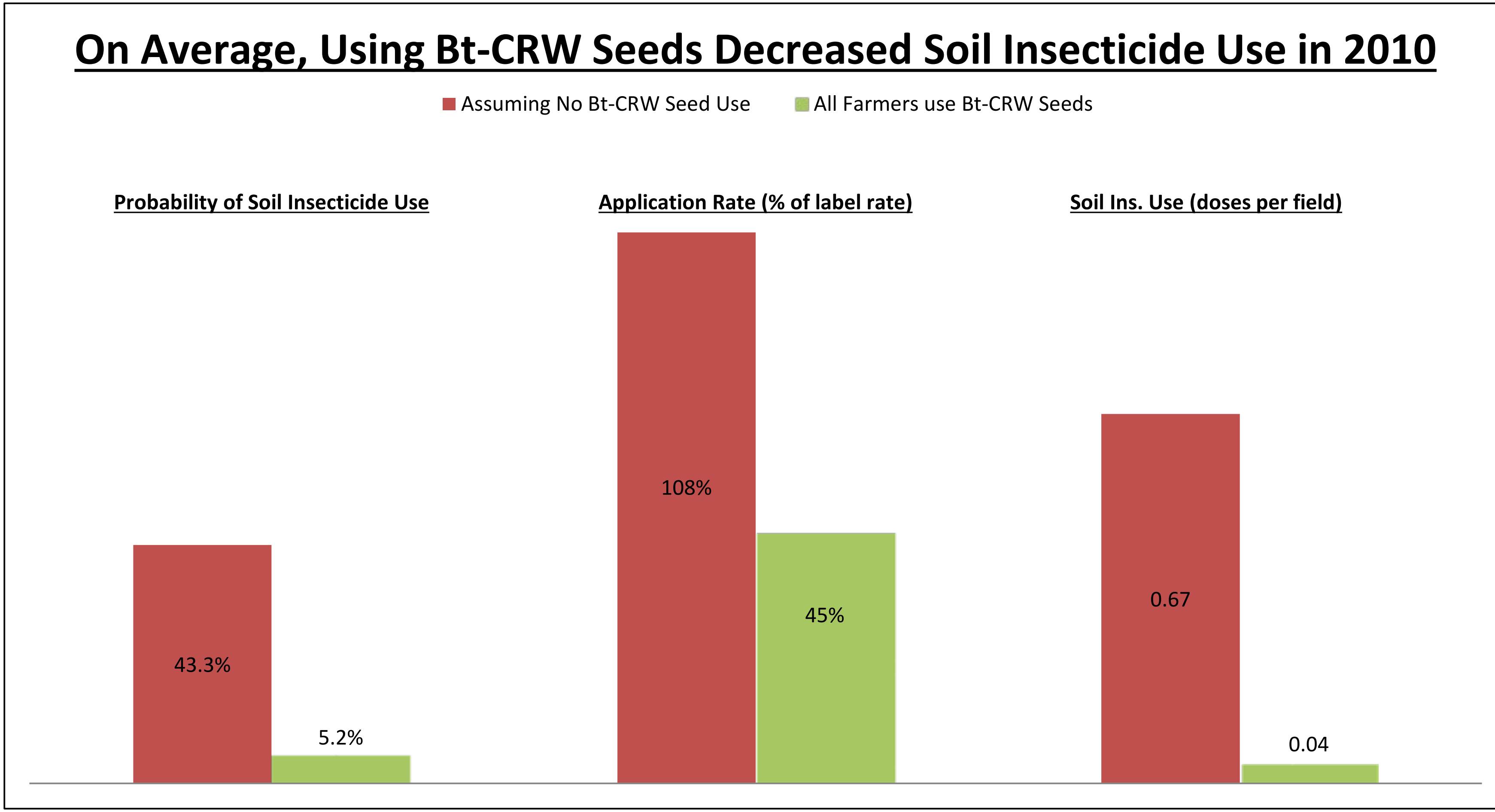
- On average, using Bt seeds increased yields by 3.9% (6.4 bu/a) in 2005 and 2% (3.3 bu/a) in 2010.
- On average, using Bt seeds decreased soil insecticide use by 32% in 2005 and 64% in 2010.
- On average, using Bt seeds increased variable profits by about $12/a.

Results



Source: Wechsler and Smith (2018)

Results



Source: Wechsler and Smith (2018)

Results

Average Yield Losses Abated, Abatement, and Control by Rootworm Treatment Strategy						
	2005			2010		
Treatment	Yield Losses Prevented (bu/a)	Abatement (%)	Rootworm Control (%)	Yield Losses Prevented (bu/a)	Abatement (%)	Rootworm Control (%)
Ins. (label rate), No Bt	3.31***	95.4***	31.2***	2.75**	96.5***	31.2***
Bt, No Ins.	8.46***	98.5***	78.1***	5.88	98.2***	65.6***
Bt, $E[\hat{I}\|Bt=1]$	8.48***	98.5***	78.1***	5.96	98.3***	66.1***

p < 0.10, ** p < 0.05, *** p < 0.01

Source: Wechsler and Smith (2018)

- On average, Bt-CRW seeds were over two times as effective as soil insecticides.
- There was not a statistically significant difference between using Bt-CRW seeds with, or without, soil insecticides.

Results

We find no evidence that insecticide use was higher on fields where resistance was likely than on fields where resistance was unlikely in 2010. In other words, we did not find evidence that rootworm resistance was widespread in our study region, over the course of our study period.

	Expression	Gumbel	Exponential	Logistic
Structural Parameters		(2,494 Observations)		
Efficacy of Soil Insecticides	a	0.37***	0.36***	0.39***
Efficacy of Bt-CRW Seeds in 2005	b_{05}	1.52**	1.46*	1.58**
Δ Efficacy of Bt-CRW from 2005 to 2010	b_{10}	−0.46**	−0.44**	−0.48**
Δ Efficacy of Bt-CRW due to Consecutive Bt-CRW Use (in 2010)	b_{Btl}	0.15	0.14	0.16

		2010		
Description	Expression	Marginal Effect	Standard Error	P-value
		(128 Observations)		
Yields (bushels per acre)[a]	$E[Y \mid E[I]]$	0.64	0.58	0.29
Abatement (%)[a]	$E[G \mid E[I]]$	0.35	0.32	0.29
Rootworm Control (%)[a]	$E[C \mid E[I]]$	4.91	5.27	0.37
Probability of Using Soil Insecticides (%)	$E[Pr(I^* > 0)]$	−6.61	6.61	0.33
Application Rate (% of label rate)	$E[I \mid I^*>0]$	−7.75	7.58	0.32
Soil Insecticide Use (% of label rate)	$E[I]$	−6.18	6.24	0.34

Source: Wechsler and Smith (2018)

Results

Expression	Label	Bt-CRW Adopters
$\frac{\partial \mathrm{E}[I_i]}{\partial b}\frac{b}{\mathrm{E}[I_i]}$	Elasticity of Demand w.r.t b	-5.60**
$\frac{\partial \Pr[I_i^* > 0]}{\partial b}\frac{b}{\Pr[I_i^* > 0]}$	Elasticity of Prob. of Demand w.r.t b	-4.78**
$\frac{\partial \mathrm{E}[I_i \mid I_i^* > 0]}{\partial b}\frac{b}{\mathrm{E}[I_i \mid I_i^* > 0]}$	Elasticity of the App. Rate w.r.t b	-0.82**
$\frac{\partial \mathrm{E}[Y_i]}{\partial b}\frac{b}{\mathrm{E}[Y_i]}$	Elasticity of Expected Yield w.r.t b	0.14
$\frac{\partial \mathrm{E}[C_i]}{\partial b}\frac{b}{\mathrm{E}[C_i]}$	Elasticity of Control w.r.t b	0.19

Source: Wechsler and Smith (2018)

- We found evidence that resistance would impact soil insecticide, if/when it developed. We did not find evidence that resistance would impact yields.
- Generally, application rates were fairly inelastic to changes in the efficacy of Bt seeds. Our findings suggest that resistance would increase the percent of Bt-adopters using soil insecticides.

Conclusions

- The results suggest that rootworm resistance was not widespread as of 2010. Future work will analyze data that is being collected for 2012, 2013, 2014 and 2016.
- The development of resistance could induce large increases in soil insecticide use, but relatively small changes in yields.
- Bt-CRW seed use provide over twice as much control as soil insecticides.
- There is no evidence that using Bt-CRW seeds with soil insecticides provides more control than using Bt-CRW seeds without soil insecticides.
- On average, planting Bt-CRW seeds would have increased yields by over 6 bushels per acre in 2005 and 3 bushels per acre in 2010.

Additional Reading

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Thank you!

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