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## Insuring the Stewardship of Bt Corn: 'A Carrot' versus 'A Stick'

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Subsidies and fines are compared to voluntary and mandatory refuge insurance (insurance for pest damage on Bt corn refuge) as mechanisms for securing grower compliance with EPA refuge mandates. A conceptual model partially ranks mechanisms. Tradeoffs between mechanisms using grower welfare, payments to growers, and monitoring frequency are quantified empirically. Grower welfare is lowest with mandatory insurance because growers pay all costs, and is highest with direct refuge subsidies because public funds or companies subsidize all costs. Assuming typical premium loads and ignoring distribution considerations, we develop monitoring budgets for fines and subsidies, above which voluntary or mandatory insurance is better.

*Key words:* biotechnology, European corn borer, refuge insurance, resistance management

### Introduction

Recent applications of genetic engineering in agriculture include the insertion of a gene from the soil bacterium *Bacillus thuringiensis* (Bt) into corn. The resulting Bt corn produces proteins that are toxic when consumed by the European corn borer (ECB) *Ostrinia nubilalis* and other lepidopterous insects. The high efficacy of Bt corn has resulted in rapid and widespread adoption since its commercial introduction in 1996. In 1999, an estimated 26% of U.S. corn acreage was planted to Bt corn [U.S. Environmental Protection Agency (EPA) 2000]. Adoption has slowed due to market uncertainties, low commodity prices, and less severe ECB infestations. Nevertheless, Bt corn still represented almost 20% of U.S. corn acreage in 2000 and 2001 (U.S. Department of Agriculture/National Agricultural Statistics Service).

The high efficacy and rapid adoption of Bt corn raise concerns that ECB will become resistant to the Bt toxin. Insects have previously developed resistance to highly effective and widely used pesticides, including Bt (Tabashnik). Growers have little incentive to voluntarily manage resistance because pests are treated as common property (Carlson and Wetzstein). Concerns about Bt resistance are heightened because Bt pesticides are natural, impose fewer environmental and human-health risks than synthetic pesticides, and are one of the few pesticides available to organic growers.

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The Environmental Protection Agency believes insect resistance management (IRM) is in the public interest and mandates IRM plans for Bt corn (U.S. EPA 1998). Current plans use a high-dose refuge strategy requiring growers to plant non-Bt corn as refuge. Refuge allows Bt-susceptible ECB to survive and mate with the few resistant ECB emerging from Bt fields, thus slowing the proliferation of resistance and prolonging the efficacy of Bt (Ostlie, Hutchison, and Hellmich). But because planting refuge restricts a grower's ability to manage ECB, growers who find Bt corn profitable are financially burdened by refuges and have little incentive to voluntarily comply. As a result, the EPA is concerned that growers may plant too little or no refuge acres.

Anonymous survey data collected by seed companies suggest 85–95% of farmers comply with the refuge requirement. The proportion of acres represented by these farmers is not clear. Furthermore, given the sensitivity of the survey questions and lack of independent verification, actual compliance is likely lower (U.S. EPA 2000).

The EPA response to compliance concerns is twofold. First, it requires Bt crop registrants to (a) submit a detailed compliance program, (b) conduct compliance surveys, and (c) implement intensified grower education in areas with compliance problems (U.S. EPA 1999b). Second, at a special workshop and Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) Scientific Advisory Panel on Bt plant pesticides, the EPA requested expert and public comment on compliance issues and methods to improve compliance, such as education, fines, refuge insurance, and sales incentives (U.S. EPA 1999a, 2000). As a result of these comments, the EPA concluded:

To achieve a high level of grower compliance, a specific program may need to be developed for Bt corn to ensure grower conformity and penalize noncompliance. A number of different compliance mechanisms have been proposed by various stakeholders, but there are uncertainties regarding many of the proposed mechanisms and that [sic] further study regarding IRM compliance is needed (U.S. EPA 2000, p. IID43).

The purpose of this study is to alleviate some of the uncertainty surrounding proposed mechanisms. We develop a refuge insurance model to compare insurance-based compliance mechanisms to more traditional mechanisms. Refuge insurance—single-peril insurance for yield loss due to ECB—ensures compliance by reducing the cost of refuge and because insurance claims can be denied to noncompliant growers. Using grower welfare, payments to growers, and monitoring frequency, subsidized and mandatory refuge insurance are compared to direct subsidies and fines.

### Conceptual Framework

Assume pest control with insecticides is not economical, a realistic assumption for refuge corn and ECB in most of the Midwest (Demetra et al.). The model can be adapted to circumstances where the assumption is not realistic. Pest damage causes proportional yield loss (Hennessy; Lichtenberg and Zilberman; Marsh, Huffaker, and Long; Saha, Shumway, and Havenner). Per acre grower returns with the conventional crop are  $\pi_0 = py(1 - \lambda) - c$ , where  $p$  is crop price,  $y$  is Bt corn yield,  $\lambda$  is yield loss due to ECB, and  $c$  is production cost.

We treat price and the production cost as known, to focus on the pertinent sources of uncertainty. Bt yield is unconditionally distributed with density  $b(y)$  to capture

uncertainty due to weather, random input availability, and other pests and pathogens. Proportional yield loss due to ECB cannot be directly observed under ordinary field conditions, but is estimated using stalk tunneling by ECB. The conditional density  $h(\lambda | s)$  captures the stochastic relation between yield loss  $\lambda$  and stalk tunneling  $s$ . The conditional density  $w(s | n)$  captures the dependence of tunneling on the pest population  $n$ . Because  $s$  depends on  $n$ , and  $\lambda$  depends on  $s$ ,  $\lambda$  also depends on  $n$ . The pest population follows the unconditional density  $v(n)$ .

If growers pay a technology fee  $T$  to purchase Bt seed, returns for a noncomplying grower planting only Bt corn are  $\pi_{Bt} = py - c - T$ . Returns for a complying grower planting the required proportion of refuge  $\phi$  are  $\pi_C(\phi) = \phi[py(1 - \lambda) - c] + (1 - \phi)[py - c - T]$ . Let  $U(\cdot)$  denote grower utility, where  $U'(\cdot) > 0$ , and  $U''(\cdot) < 0$ . Assuming  $y$  and  $\lambda$  are independent, expected utility is written as:

$$E[U(\pi)] = \int_y \int_\lambda \int_s \int_n U(\pi(y, \lambda)) b(y) h(\lambda | s) w(s | n) v(n) dn ds d\lambda dy.$$

$C_C$ , the unique cost to a grower of voluntarily complying with the refuge requirement, is implicitly defined by:

$$(1) \quad E[U(\pi_C(\phi) + C_C)] = E[U(\pi_{Bt})].$$

This compliance cost is a grower's incentive to violate the refuge mandate. If  $C_C \leq 0$ , growers voluntarily comply, a case not of interest here. If  $C_C > 0$ , Bt corn increases average profit, reduces profit risk, or both, and growers do not voluntarily comply.

Given  $s$ , the monetary value of the expected loss due to pest damage is:

$$L(s) = pE[y|E[\lambda|s]] = p \int_y y b(y) dy \int_\lambda \lambda h(\lambda | s) d\lambda.$$

The indemnity  $I(s)$  equals the expected loss minus the deductible  $D$ , and is censored at zero:

$$(2) \quad I(s) = \text{Max}\{L(s) - D, 0\}.$$

Returns for a complying grower receiving the indemnity  $I(s)$  on refuge acres without paying a premium are  $\pi_I(\phi) = \phi[py(1 - \lambda) - c + I(s)] + (1 - \phi)[py - c - T]$ . The actuarially fair premium  $M$  is the expected value of this indemnity:

$$(3) \quad M = \int_n \int_s I(s) w(s | n) v(n) ds dn.$$

The actual premium is  $\phi M(1 + \beta)$ , where  $\beta$  is the load required to cover adjustment, monitoring, and administrative costs.

The motivation for using a deductible with refuge insurance is quite different than for traditional insurance. The deductible for refuge insurance serves as a policy instrument for managing compliance incentives and not as a mechanism for managing moral hazard or adverse selection.

### *Voluntary Mechanisms*

Refuge insurance can secure compliance with the refuge requirement if the insurance benefit meets or exceeds any profit and risk benefit provided by Bt corn, plus the

adjustment, monitoring, and administrative costs of the insurance. In this case,  $E[U(\pi_I(\phi) - \phi M(1 + \beta))] > E[U(\pi_{Bt})]$ . The unique maximum load  $\beta_v$  a grower is willing to pay for voluntary insurance and still comply with the refuge mandate is implicitly defined by:

$$(4) \quad E[U(\pi_I(\phi) - \phi M(1 + \beta_v))] = E[U(\pi_{Bt})].$$

If the actual load  $\beta$  exceeds this maximum load  $\beta_v$ , the grower will not voluntarily buy insurance and comply, nor will a private market for refuge insurance exist. However, if  $\beta_v \geq \beta$ , the grower will voluntarily buy insurance and comply, and consequently a private market for refuge insurance should emerge. An insurance market for ECB loss currently does not exist, providing a strong indication that the risk benefit of refuge insurance does not cover the adjustment, monitoring, and administrative costs. In this case, refuge insurance requires subsidization to secure grower compliance. The minimum subsidy needed is the difference between the actual load and the maximum load growers are willing to pay:  $\phi M(\beta - \beta_v)$ .

A direct refuge subsidy given to growers when they purchase Bt corn (e.g., as a price reduction for non-Bt seed) can secure voluntary compliance. Monitoring is required because growers can accept the subsidy and still plant only Bt corn. Let  $\alpha$  be the probability a grower is inspected. Assume inspection correctly identifies compliant and non-compliant growers, and that noncompliant growers must return the subsidy. The unique minimum subsidy which secures compliance,  $S_s > 0$ , is implicitly defined by:

$$(5) \quad E[U(\pi_C(\phi) + S_s)] = E[\alpha U(\pi_{Bt}) + (1 - \alpha)U(\pi_{Bt} + S_s)].$$

The subsidy works only if  $E[U(\pi_C(\phi) + S_s)] > E[U(\pi_{Bt})]$ , which implies it exceeds the cost of compliance. Because  $S_s$  is a decreasing function of  $\alpha$ , it is possible to optimally balance the cost of direct subsidies with the cost of monitoring.

### Compulsory Mechanisms

If the load growers are willing to pay does not cover the actual load, and the political will to subsidize a voluntary compliance program does not exist, growers could be required to purchase refuge insurance. With mandatory insurance, growers buying Bt corn pay an additional  $\phi M(1 + \beta)$  for insurance, whether they want it or not. However, noncompliance can be optimal even with mandatory insurance. If the deductible is large and the technology fee is small, Bt corn is relatively cheap and eliminates losses even when the insurance deductible is not met. Thus, mandatory insurance secures compliance only if  $E[U(\pi_I(\phi) - \phi M(1 + \beta))] \geq E[U(\pi_{Bt} - \phi M(1 + \beta))]$ . As both  $I(s)$  and  $E[U(\pi_I(\phi))]$  are non-increasing in the deductible, given the load, a unique maximum deductible ( $D_M$ ) exists for mandatory refuge insurance that secures compliance:

$$(6) \quad D_M = \text{Max}[D | E[U(\pi_I(\phi) - \phi M(1 + \beta))] = E[U(\pi_{Bt} - \phi M(1 + \beta))]].$$

With preferences exhibiting constant absolute risk aversion (CARA), mandatory insurance can secure compliance without a subsidy by setting the deductible  $D \leq D_M$  to ensure  $E[U(\pi_I(\phi))] \geq E[U(\pi_{Bt})]$ . Whatever load is required to cover adjustment, monitoring, and administrative costs can then be charged without affecting compliance incentives,

because  $E[U(\pi_I(\phi) - \phi M(1 + \beta))] \geq E[U(\pi_{Bt} - \phi M(1 + \beta))]$  implies  $E[U(\pi_I(\phi))] \geq E[U(\pi_{Bt})]$  for nonrandom  $\phi M(1 + \beta)$  and CARA preferences.

With more general preferences, the deductible  $D$  can be subsidized to guarantee compliance. The magnitude of this subsidy depends on the expected loss. If  $L(s) < D_M$ , no payment is needed. If  $D > L(s) \geq D_M$ , the necessary payment is the difference between the loss and maximum deductible,  $L(s) - D_M$ . If  $L(s) \geq D$ , the payment is the difference between the actual deductible and maximum deductible,  $D - D_M$ . On average, the payment is  $\phi \Pr[D > L(s) \geq D_M](L(s) - D_M) + \phi \Pr[L(s) \geq D](D - D_M)$ .

Compliance can also be secured by combining fines with monitoring. Again, if  $\alpha$  is the inspection probability, inspection correctly identifies compliant and noncompliant growers, and inspected noncompliant growers pay a fine. The unique minimum fine ( $F$ ) which secures compliance is defined by:

$$(7) \quad E[U(\pi_C(\phi))] = E[\alpha U(\pi_{Bt} - F) + (1 - \alpha)U(\pi_{Bt})].$$

The minimum fine is decreasing in  $\alpha$ , so compliance can be assured with a high fine and infrequent monitoring, within the political, legal, and financial constraints of such a policy. Alternatively, given a mandated fine  $F$ , equation (7) can be explicitly solved for the minimum inspection rate  $\alpha$  needed to secure compliance.

### Comparing Mechanisms

Each mechanism uses a different approach to secure compliance. Voluntary insurance uses subsidized insurance as a "carrot" to secure grower compliance. Fines rely on monitoring and penalties for noncompliance as a "stick." By forcing growers to buy insurance and using the indemnity to entice compliance, mandatory insurance combines a "carrot" with a "stick." Refuge subsidies also mix a "carrot" and a "stick" by using a payment to entice growers to comply, but withdraw the payment if they are caught cheating.

Each mechanism can be compared based on payments to growers, the monitoring frequency, and grower welfare. The payment to growers is denoted by  $\phi M(\beta - \beta_v)$  for voluntary insurance. For mandatory insurance and CARA preferences, no payment to growers is required. With more general preferences, the expected payment securing compliance is specified as  $\phi \Pr[D > L(s) \geq D_M](L(s) - D_M) + \phi \Pr[L(s) \geq D](D - D_M)$ . Direct subsidies require at least  $S_g$  in payments to growers, while fines require no payments. In general, we cannot rank these payments, but payments to growers are always minimized with a fine scheme and, if preferences are CARA, with mandatory insurance.

Adjustment, monitoring, and administrative costs are embodied in the load with both insurance programs, so payments to growers already account for these costs. Fines and subsidies require monitoring, and the cost of this monitoring depends on the inspection frequency; for the same frequency, monitoring costs should be comparable.

When payments to growers are the minimum needed to secure compliance, grower welfare with a direct subsidy is higher than with voluntary insurance, and is higher with voluntary insurance than with a fine [compare equations (4), (5), and (7)]. By assumption, growers are better off with voluntary insurance than with mandatory insurance [compare equations (4) and (6)]. In general, growers can be better or worse off with mandatory insurance than with a fine.

Growers do best with a subsidy because, while they are compensated to plant a refuge, they can still not plant the refuge, and then forfeit the subsidy only if they are inspected and caught cheating. Because monitoring is intermittent, the subsidy must exceed the cost of compliance, which drives average profit above what is obtained from planting only Bt corn without accepting a subsidy. With insurance, growers receive a payment only for losses on the refuge. If insurance is voluntary, growers must be given an incentive to buy the insurance. This incentive must make them as well off as when planting only Bt corn without insurance, but will still be less than what they receive with the subsidy program. Making insurance mandatory eliminates this incentive payment, but growers will not be as well off as when planting only Bt corn, because they must forfeit the insurance indemnity to do so. Growers receive no payments with a fine, so if they comply, average profit must be lower than when they plant only Bt corn, which is what they receive with voluntary insurance.

Based on these comparisons, one cannot say one program dominates another in the Pareto sense. Subsidies are good for growers, but may require substantial expenditures from whoever pays the subsidy, plus someone must pay the monitoring costs. Voluntary insurance is also good for growers, but may require subsidy payments, particularly if the insurance has a small risk benefit and requires a large load. Mandatory insurance can eliminate payments to growers, but because growers pay both the monitoring and insurance costs, it may substantially reduce grower welfare relative to other programs. Growers are not as well off with fines as with voluntary insurance and direct subsidies, and, though payments to growers are unnecessary, monitoring costs may be high. To reduce some of the ambiguity concerning the relative costs and benefits of each compliance program, the conceptual model is parameterized using recent field data.

### Empirical Model

For  $b(y)$ , the distribution of pest-free yield, we use a beta density and parameters consistent with dryland corn in Boone County, Iowa. Minimum and maximum yields are 0 and 212 bushels/acre and shape parameters are 3.26 and 1.61, giving a mean of 141.9 bushels/acre and a standard deviation of 41.2 bushels/acre. Following the empirical results of Showers et al., pest-free yield is assumed uncorrelated with the ECB population.

State average ECB populations (second-generation ECB per plant), derived from data described by Bullock and Nitsi, were available for Illinois (1943–1984, 1987–1996), Minnesota (1963–1998), and Wisconsin (1963–1998). Calvin reports similar data for Boone County, Iowa, and Hall County, Nebraska, for 1960–1969 using Hill et al. Because populations must be positive, lognormal and gamma distributions were estimated via maximum likelihood. Time trends, found to be statistically insignificant at the 5% level, were removed. The lognormal distribution was employed because it had the largest maximized value for the likelihood function with the same number of parameters (Pollak and Wales). The Durbin-Watson test indicated no autocorrelation in the errors, in agreement with the findings of Chiang and Hodson; Chiang et al.; and Showers et al. As a result, an unconditional lognormal distribution was used for  $v(n)$ , the distribution of the annual ECB larval population. Table 1 reports parameter estimates for each location.

Data were obtained from Monsanto on the average ECB larvae per plant and average tunneling (cm) from Bt field trials conducted in nine states in 1997. Because Bt corn

**Table 1. Maximum-Likelihood Estimates of the Mean and Coefficient of Variation for  $v(n)$ , the Lognormal Density of ECB Larvae per Plant**

Location	Mean	Standard Error	Coefficient of Variation	Standard Error
Illinois <sup>a</sup>	1.12	0.12	0.71	0.09
Minnesota <sup>a</sup>	0.81	0.12	0.94	0.15
Wisconsin <sup>a</sup>	0.55	0.09	1.06	0.18
Boone County, Iowa <sup>b</sup>	0.85	0.24	0.92	0.28
Hall County, Nebraska <sup>b</sup>	1.80	0.30	0.53	0.13

<sup>a</sup> Based on state data from Bullock and Nitsi.

<sup>b</sup> Based on county data from Calvin.

**Table 2. Maximum-Likelihood Parameter Estimates for  $w(s|n)$ , the Lognormal Distribution of Tunneling Conditional on the ECB Larval Population, and for  $h(\lambda | s)$ , the Distribution of Proportional Yield Loss Conditional on Tunneling**

Lognormal Distribution of $w(s n)$ <sup>a</sup>			Cobb-Douglas Model of $h(\lambda   s)$ <sup>b</sup>		
Parameter	Estimate	Std. Error	Parameter	Estimate	Std. Error
$a_1$	2.56	0.839	$\kappa$	0.033	0.015
$a_2$	5.65	1.022	$z$	0.660	0.188
$b_0$	3.40	0.756	$\eta$	0.102	0.012
$b_1$	1.73	0.553			

<sup>a</sup> The conditional mean of  $w(s|n)$  is  $a_1n + a_2\sqrt{n}$ , and the conditional standard deviation is  $b_0 + b_1n$ .

<sup>b</sup> The parametric form of the model is  $\lambda = \kappa s^z + \eta \epsilon$ , where  $\epsilon \sim N(0, 1)$ .

completely controlled ECB, only data from 211 non-Bt fields were used for estimation. Incidence of tunneling must be positive; therefore, maximum-likelihood models were estimated using a gamma and lognormal density for the distribution of tunneling conditional on ECB larvae. A linear model was used for the standard deviation.

Combinations of linear, quadratic, negative exponential, square root, and hyperbolic terms were evaluated for mean tunneling as a function of the larval population, imposing a zero intercept in all cases. The best fitting model ( $R^2 = 0.822$ ) included both a linear and square root term, and used the lognormal distribution since it had the largest maximized value for the likelihood function (Pollak and Wales). Thus, tunneling has a lognormal density with conditional mean  $a_1n + a_2\sqrt{n}$  and conditional standard deviation  $b_0 + b_1n$ , where  $a_1$ ,  $a_2$ ,  $b_0$ , and  $b_1$  are estimated parameters (reported in table 2).

Data from experiments conducted in 1995 near Ames, Iowa, were used to estimate the distribution of proportional yield loss conditional on stalk tunneling. Non-Bt corn and a Monsanto Bt event in the same hybrid were exposed to an artificial ECB infestation and a natural infestation with no pest control, and with two different insecticides. Bt plots had almost no tunneling, so their average yield was used to calculate proportional yield loss.



Nonlinear maximum-likelihood models were estimated for mean proportional yield loss as a function of tunneling, including negative exponential, logarithmic, and combinations of linear and square root terms. A univariate Cobb-Douglas model gave the best fit ( $R^2 = 0.347$ ):  $\lambda = \kappa s^z + \eta \varepsilon$ , where  $\kappa$ ,  $z$ , and  $\eta$  are parameters to estimate, and  $\varepsilon \sim N(0, 1)$  is a random error. The maximum-likelihood parameter estimates are presented in table 2. The low correlation between tunneling and yield loss, and hence the low  $R^2$ , is typical (Berry and Campbell; Lynch, Robinson, and Berry) because factors other than tunneling contribute to deviations from pest-free yield (Bode and Calvin; Jarvis et al.).

Due to random environmental factors, some (27%) of the observed yield losses were negative. The estimated model preserves this property of the data. With the estimated parameters, expected yield loss exceeds 100% at 179.6 cm of tunneling, and the probability that realized tunneling exceeds 100% reaches 5% at 135.9 cm of tunneling. Reported results censored realized losses at 100%, but because this level of tunneling is unlikely for the estimated model, the constraint was never binding.

### Grower Preferences

As an approximation of farmers' preferences, CARA is assumed. The coefficient of absolute risk aversion ( $R_a$ ) was set so that the risk premium is a reasonable percentage of the standard deviation of per acre returns (Babcock, Choi, and Feinerman). Bt corn and refuge insurance did not greatly affect the standard deviation of returns, even when the ECB population mean was varied from 0.5 to 2.0 and its coefficient of variation ranged from 0.5 to 1.25. For the five locations, the standard deviation ranged from \$83.12 to \$78.39, with an average of \$81.29.  $R_a = 0.005057$  corresponds to a risk premium equal to 20% of \$81.29, and is consistent with moderate risk aversion.

Let  $CE_i$  be the certainty equivalent for  $i \in \{C, I, Bt\}$ . With CARA utility, equations (1), (4), (5), and (7) can be solved explicitly for the quantities of interest (i.e., compliance cost, maximum load, minimum subsidy, and minimum fine, respectively):

$$(8) \quad C_C = CE_{Bt} - CE_C,$$

$$(9) \quad \beta_V = ((CE_I - CE_{Bt})/\phi M) - 1,$$

$$(10) \quad S_S = [\ln(\exp(R_a C_C) - 1 + \alpha) - \ln(\alpha)]/R_a,$$

$$(11) \quad F = [\ln(\exp(R_a C_C) - 1 + \alpha) - \ln(\alpha)]/R_a.$$

While  $S_S$  and  $F$  are generally not equal, they are here because of the nature of CARA preferences. Solving equation (6) explicitly for the maximum deductible  $D_M$  is not possible, but with CARA preferences, a unique  $D_M$  exists and can be found numerically. Following EPA requirements for unsprayed refuge acres, we set  $\phi = 0.20$ .

Because integrating to obtain expected utilities and to find the premium defined by equation (3) is analytically intractable for the specified distributions, Monte Carlo integration was used (Greene, pp. 192–95). Using algorithms from Press et al., a C++ program was employed to draw the required random variables; 50,000 random variates from each probability density were sufficient for estimates to stabilize.

## Empirical Results

### *Fair Premiums and the Cost of Compliance*

With the estimated damage model, average yield loss due to ECB ranged from 9.3% in Wisconsin to 17.5% in Hall County, Nebraska, which exceeds the average annual U.S. yield loss of 6.4% estimated by Calvin. The model was estimated with data from one location and year, for a hybrid known to be susceptible to ECB damage, using rather high artificial infestations. To calibrate the model, average damage is proportionally reduced, holding the coefficient of variation constant to preserve observed variability. Reducing damage by 50% gives average damages ranging from 4.6% in Wisconsin to 8.7% in Hall County, Nebraska, damage percentages which are closer to Calvin's estimate.

The current technology fee of about \$10/acre seems a reasonable deductible, because refuge corn must lose this much before it is less profitable than Bt corn. With a corn price of \$2/bushel and mean yield of 141.9 bushels/acre, a \$10 deductible implies a 3.5% loss. Table 3 reports actuarially fair premiums for each location with different deductibles. Premiums are reported as  $\phi M$  to spread the cost over the whole field.

Because gross revenue is linear in price and pest-free yield, a price increase with a constant mean and variance of yield has the same impact as a mean yield increase with a constant price and yield variance. As gross revenue increases, premiums increase more than proportionally because the value of losses increases and it becomes more likely that losses exceed the deductible. As a factor to adjust premiums, empirically the arc elasticity of the premium with respect to the price or mean yield is about 1.4.

The cost of compliance ( $C_c$ ) reported in table 3 is largest in Hall County, Nebraska (\$2.35), where the ECB mean population is highest, and is lowest in Wisconsin (\$0.31). To indicate the sensitivity of  $C_c$  to key parameters, increasing the corn price 25% to \$2.50/bushel increases  $C_c$  about 25%, and "doubling" risk aversion to a 40% risk premium ( $R_a = 0.011078$ ) decreases  $C_c$  by approximately 30%.

### *Voluntary Mechanisms*

Table 3 also reports  $\beta_v$ , the maximum premium load a grower is willing to pay and still comply when refuge insurance is voluntary. Because  $\beta_v < 0$  for all locations and deductibles, voluntary insurance requires a premium subsidy to secure compliance, even if premiums are actuarially fair. When  $\beta_v < -1$ , as occurs with a \$20 and a \$30 deductible, even free insurance does not secure voluntary compliance, and growers must be paid to accept the insurance and comply.

Sensitivity analysis explored these results. The ECB population mean was varied from 0.5 to 2.0, the coefficient of variation from 0.5 to 1.25,  $R_a$  from 0.001232 to 0.011078 (a risk premium representing 5%–40% of the profit standard deviation), and the price of corn from \$1.80 to \$2.50. The magnitude of  $\beta_v$  changes, but not the finding that  $\beta_v < 0$ , with  $\beta_v < -1$  in most cases, especially with higher deductibles.

As no market for ECB insurance previously existed or has recently emerged,  $\beta_v < 0$  is not surprising. Because Bt corn increases average profit in the examples,  $\beta_v < -1$  is also not surprising. With fair premiums, refuge insurance has no effect on average profit, but when fair premiums are loaded, refuge insurance decreases average profit. Insurance provides a risk benefit, but so can Bt corn. As a result, for refuge insurance

**Table 3. Actuarially Fair Premiums by Location, Assuming CARA Utility with a 20% Risk Premium ( $R_a = 0.005057$ )**

Description	Deductible	Location				
		Illinois	Minnesota	Wisconsin	Boone Co., Iowa	Hall Co., Nebraska
		----- (\$/acre) ----->				
Compliance Welfare ( $CE_C$ )	—	74.05	74.72	75.23	74.65	73.19
Compliance Cost ( $C_C$ )	—	1.49	0.81	0.31	0.89	2.35
Maximum Deductible ( $D_M$ )	—	13.44	14.58	17.96	14.37	13.47
Fair Premium ( $\phi M$ )	10	2.03	1.36	0.90	1.42	2.98
Fair Premium ( $\phi M$ )	20	0.76	0.43	0.24	0.46	1.37
Fair Premium ( $\phi M$ )	30	0.27	0.14	0.07	0.15	0.55
Fair Premium ( $\phi M$ )	$D_M$	1.48	0.81	0.31	0.88	2.34
Maximum Load ( $\beta_v$ )	10	-0.73	-0.60	-0.34	-0.62	-0.78
Maximum Load ( $\beta_v$ )	20	-1.95	-1.89	-1.31	-1.91	-1.71
Maximum Load ( $\beta_v$ )	30	-5.58	-5.76	-4.49	-5.76	-4.25

to secure compliance, high subsidies are required to compensate growers for the higher average profit foregone on refuge acres.

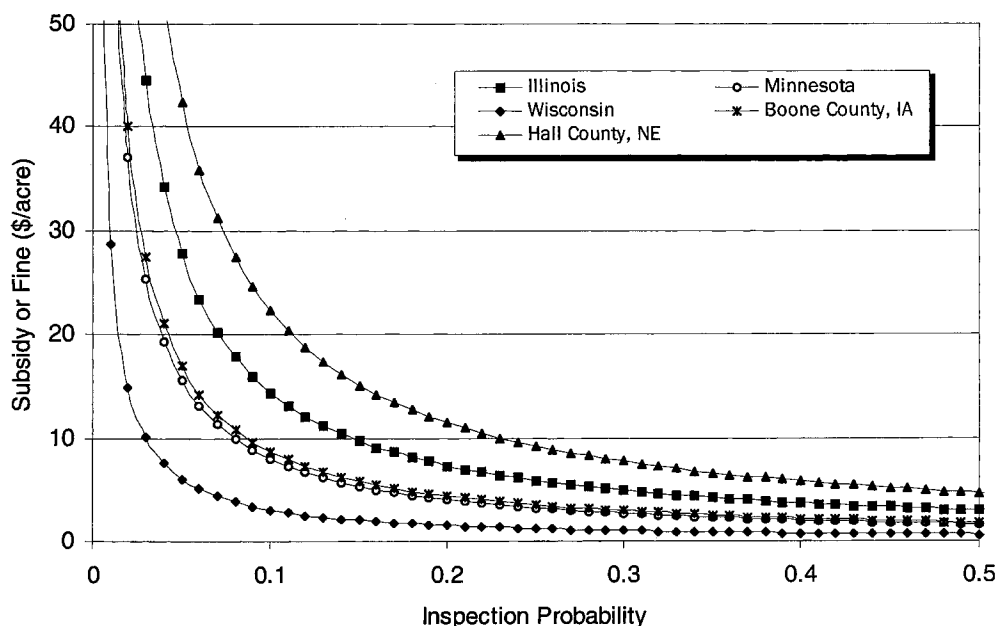
The Agricultural Risk Protection Act of 2000 has led to a substantial increase in the premium subsidy for federal crop insurance programs. As a result, many growers have crop insurance coverage on their Bt corn fields. This crop insurance should reduce the refuge insurance premium, if large losses due to ECB are covered by crop insurance and not refuge insurance. Crop insurance will then reduce demand for voluntary refuge insurance, especially if the refuge and the Bt corn can be insured as separate units. Both of these effects would change the premium subsidy needed for voluntary refuge insurance to secure compliance.

Based on our empirical analysis, the effect of crop insurance on fair premiums is greatest in Hall County, Nebraska, where ECB pressure is highest. However, ECB losses are rarely high enough to trigger crop insurance payments; thus, incorporating crop insurance into the analysis has little effect on the findings. At the 65% coverage level, crop insurance reduces fair refuge insurance premiums less than \$0.01/acre for all deductibles, and less than \$0.10/acre with 75% coverage. The effect on the premium subsidy needed for refuge insurance to secure compliance is similar.

Figure 1 shows the direct refuge subsidy required to secure compliance for each of the five locations examined. At low levels of monitoring, the subsidy rapidly decreases as the inspection rate increases—for example, falling more than 50% when the rate increases from 5% to 10%. A large subsidy is required at low inspection rates because the payoff to accepting the subsidy and complying must exceed the payoff to accepting the subsidy and cheating, with some probability of being caught and having to return the subsidy.

### *Compulsory Mechanisms*

For CARA utility with a 20% risk premium, table 3 reports  $D_M$  (the maximum deductible that secures compliance with mandatory insurance) and the associated fair premium.  $D_M$  exceeds the assumed \$10/acre technology fee. Comparing expected profit for Bt corn and for insurance without a deductible suggests this outcome is always likely. With



**Figure 1. Minimum subsidy ( $S_s$ ) or fine ( $F$ ) required to secure compliance at each location, assuming CARA utility with a 20% risk premium ( $R_a = 0.005057$ )**

CARA utility, mandatory insurance with a \$10 deductible secures compliance, but not with a \$20 or a \$30 deductible.

Figure 1 plots the minimum fines which secure compliance at each location. Large fines are needed at low inspection rates, so that the expected cost of cheating is sufficiently high to prevent noncompliance. For example, the minimum fines with a 3% monitoring frequency range from about \$10/acre in Wisconsin to about \$66/acre in Hall County, Nebraska; but with a 30% monitoring frequency, the minimum fines range from approximately \$1 to \$8/acre in these same locations.

### *Program Comparisons*

Using payments to growers, grower welfare, and monitoring frequency, table 4 compares compliance programs assuming CARA utility. In these terms, no program Pareto dominates another. As an alternative, the net benefit of each program is calculated as grower welfare minus both payments to growers and the cost of additional monitoring. The insurance programs include monitoring costs in the premium load, but the direct subsidy and the fine program require additional monitoring costs. Lacking information on the cost of this additional monitoring, the net benefit of the direct subsidy and fine programs exclusive of additional monitoring costs is calculated. Unlike the Pareto criterion, this net benefit criterion ignores the distribution of benefits and costs. The last column of table 4 reports the net benefits of each program using this criterion. The net benefit exclusive of additional monitoring costs is the same for the direct subsidy and fine programs because, with CARA utility, the subsidy expenditure exactly offsets the increase in grower welfare. Consequently, whichever program has lower monitoring costs is more efficient.

Table 4. Comparison of Compliance Programs Assuming CARA Utility

Program	Payment to Growers	Grower Welfare	Frequency of Additional Monitoring	Net Benefit, Excluding Additional Monitoring Costs
Voluntary Insurance	$\phi M_V(\beta - \beta_V)$	$CE_{Bt}$	0	$CE_{Bt} - \phi M_V(\beta - \beta_V)$
Direct Subsidy	$S_S$	$CE_{Bt} - C_C + S_S$	$\alpha$	$CE_{Bt} - C_C$
Mandatory Insurance	0	$CE_{Bt} - \phi M_M(1 + \beta_M)$	0	$CE_{Bt} - \phi M_M(1 + \beta_M)$
Fines	0	$CE_{Bt} - C_C$	$\alpha$	$CE_{Bt} - C_C$

Notes:  $M_V$  and  $M_M$  are actuarially fair premiums, and  $\beta$  and  $\beta_M$  are loads for voluntary and mandatory insurance.

Table 5. Comparison of Net Benefits (\$/acre) by Location, Excluding Additional Monitoring Costs for Direct Subsidies or Fines, Assuming a Premium Load of 24.5% and CARA Utility with a 20% Risk Premium ( $R_a = 0.005057$ )

		Location				
Net Benefit Difference	Deductible	Illinois	Minnesota	Wisconsin	Boone Co., Iowa	Hall Co., Nebraska
		<----- (\$/acre) ----->				
<b>Voluntary vs. Mandatory Insurance:</b>						
$[\phi M_M(1 + \beta) - \phi M_V(\beta_M - \beta_V)]$	10	-0.13	-0.13	-0.14	-0.13	-0.16
	20	0.18	0.09	0.02	0.10	0.24
	30	0.27	0.16	0.06	0.17	0.43
<b>Direct Subsidy or Fine vs. Voluntary Insurance:</b>						
$[\phi M_V(\beta - \beta_V) - C_C]$	10	0.49	0.33	0.22	0.34	0.72
	20	0.18	0.10	0.06	0.11	0.33
	30	0.08	0.03	0.02	0.04	0.13
<b>Direct Subsidy or Fine vs. Mandatory Insurance:</b>						
$[\phi M_M(1 + \beta_M) - C_C]$	$D_M$	0.36	0.19	0.07	0.21	0.56

For ranking the other programs, the first column of table 5 reports the difference in net benefits, exclusive of monitoring costs. These differences imply intuitive conclusions. For example, voluntary insurance tends to be more efficient than mandatory insurance when it has a lower load or actuarially fair premium, and when the willingness to pay for voluntary insurance is high. Similarly, a direct subsidy or fine tends to be more efficient than either type of insurance when the actuarially fair premium or the insurance load is high, and the willingness to pay for voluntary insurance or the cost of compliance is low.

For many crop insurance products [e.g., Multiple-Peril Crop Insurance (MPCI)], 24.5% is the federally approved premium subsidy provided to cover the cost of insurance above actuarially fair premiums. Table 5 empirically compares the efficiency of the different programs using 24.5% as the premium load for voluntary and mandatory insurance ( $\beta$  and  $\beta_M$ , respectively). Three different deductibles are considered for voluntary insurance, while mandatory insurance uses  $D_M$ , the maximum deductible that guarantees compliance.

Based on the results from table 5, with a 24.5% load, mandatory insurance is more efficient than voluntary insurance when the deductible for voluntary insurance is less

than  $D_M$ . But voluntary insurance is more efficient when it has a deductible greater than  $D_M$ . Sensitivity analysis with loads ranging from 10% to 150% found this result to be robust, with the magnitude of the efficiency difference increasing with the load.

With a \$10 deductible, the Monte Carlo estimated probability that the loss will exceed the deductible ranges from 59% to 96% for the modeled locations. With a deductible of  $D_M$  at each location, the probabilities range from 21% to 87%, and with a \$30 deductible, the probability ranges between 4% and 26%. The low deductible required for mandatory insurance to be more efficient than voluntary insurance implies frequent claim adjustment in most areas, and so a high load. With higher deductibles requiring less frequent claim adjustments, voluntary insurance is more efficient than mandatory insurance because load subsidies to growers are reduced.

Table 5 also reports the net benefits of a direct subsidy or fine relative to voluntary and mandatory insurance with a 24.5% load. Monitoring costs are not included in the net benefits for the direct subsidy or fine programs. As a result, the reported values imply a maximum monitoring budget for a direct subsidy or fine program; when monitoring costs are below the reported values, a direct subsidy or fine program is more efficient than insurance for enforcing compliance. However, because regulators can always choose an inspection rate where the cost of monitoring is less than the budget indicated in table 5, they can likewise find an inspection rate such that a direct subsidy or fine program is more efficient than either voluntary or mandatory insurance. The only constraint is that the fine or subsidy implied by the maximum inspection rate be politically and legally feasible.

With a premium load of 24.5%, the implied monitoring budgets in table 5 for a \$30 deductible range from \$0.02/acre in Wisconsin to \$0.13/acre in Hall County, Nebraska. These budgets are per acre of all corn, not per acre of inspected refuge corn. For other loads, the results in table 3 can be used with the equations in column 1 of table 5 to generate more budgets.

Per acre loads collected for voluntary insurance put this monitoring budget into perspective. Using premiums from table 3 for a \$30 deductible in Hall County, Nebraska, a 24.5% load would collect \$0.13/acre, which equals the monitoring budget reported in table 5 for Hall County, Nebraska, with a \$30 deductible. This result holds for other deductibles and locations as well—the load with voluntary insurance is slightly larger, but the difference is less than \$0.01/acre. Thus, for voluntary insurance to be more efficient than direct subsidies and fines, administrative and adjustment costs must be low or the monitoring cost must be lower than with direct subsidies or fines.

The small difference between the collected insurance load and the maximum budget for a direct subsidy or fine program is representative of all locations and premium loads evaluated, and robust under extensive sensitivity analysis—the maximum found was less than \$0.10/acre. This result occurs because ECB refuge insurance only minimally reduces the standard deviation of returns. With a \$10 deductible, the greatest reduction in the standard deviation was 1.6% in Wisconsin.

The minor impact of refuge insurance on the variability of grower returns may seem counterintuitive. Yet, as demonstrated by Horowitz and Lichtenberg, and by Pannell, controlling or eliminating a pest can have surprising effects on yield variability. As noted, proportional pest damage functions are widely used in conceptual and empirical analyses. However, because pest damage is proportional to pest-free yield, total losses due to pests tend to be greater when pest-free yields are high and vice versa, allowing

damages to be positively correlated with returns. Thus insurance compensating growers for pest losses tends to pay higher indemnities when yields and returns are high, and vice versa. As a result, pest or refuge insurance does not greatly reduce the variability of returns, and the risk benefit of insurance is small.

## Discussion and Conclusion

The EPA has mandated refuge requirements for Bt corn to reduce the chance of the European corn borer developing resistance. Still, the EPA and other stakeholders are concerned that growers may choose not to comply with these requirements without appropriate incentives. While many compliance programs have been proposed (e.g., education, fines, refuge insurance, and sales incentives), little research has been conducted to evaluate alternatives. The purpose of this study is to begin to fill this void by examining a direct subsidy, a fine, and voluntary and mandatory insurance programs. Each program is assessed based on grower welfare, payments to growers, and monitoring frequency.

Our findings show all four programs can be designed to offer growers the appropriate incentives to comply. However, each program distributes costs differently, so no single program Pareto dominates all others. A direct subsidy program is best for growers, but someone must pay subsidy and monitoring costs. A fine program eliminates payments to growers, but also lowers grower welfare—particularly when compared to a direct subsidy—and does not eliminate monitoring costs. Insurance internalizes the cost of monitoring into the cost of the insurance, but subsidies are still required before growers will buy this insurance voluntarily, and grower welfare is not as high as with a direct subsidy.

Ignoring the distributional consequences of each program, we find a number of empirical regularities. With high deductibles, growers require a smaller incentive to voluntarily purchase insurance, which reduces payments to growers but not grower welfare. As a result, mandatory insurance is only better than voluntary insurance when deductibles are low. Because the risk benefit of insurance for ECB losses is small, for practical insurance loads (in excess of 20% of the actuarially fair premium), a direct subsidy or fine program is better than voluntary insurance when monitoring costs are less than about 95% of the monitoring, administrative, and adjustment costs of insurance. Therefore, a direct subsidy or fine will tend to be more efficient unless insurance providers have relatively low administrative and adjustment costs or lower monitoring costs. Crop insurance has little empirical effect and does not change the general results. With utility exhibiting constant absolute risk aversion, a direct subsidy and a fine program are equivalent. For more general risk preferences, one will typically be more efficient than the other.

A key policy question remaining to be addressed is the distributional issue of who should be responsible for bearing the cost of compliance with refuge mandates. Growers benefit from resistance management because it preserves the efficacy of Bt corn and helps to alleviate a potential tragedy of the commons. The public also benefits from resistance management because Bt corn can reduce the use of pesticides that are hazardous to human health and the environment. Consequently, programs shifting the entire burden of compliance onto growers (fines and mandatory insurance) may not be appropriate. The mechanisms explored here provide a variety of alternatives for sharing the cost of obtaining the benefits of resistance management for Bt corn.

Another important question remaining to be answered is whether or not the cost of implementing a resistance management program exceeds the benefits of that program. The wealth of literature on resistance management convincingly demonstrates a benefit, but we are unaware of studies establishing the cost of implementing programs to secure those benefits. Without estimates of these costs, the extent to which resistance management programs improve welfare remains unclear.

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