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Abstract

The EPA has imposed mandatory refuge requirements for Bt crops to prolong the efficacy of Bt. Growers have no economic incentive to plant the required refuge because refuge crops are on average less productive and more risky. This paper evaluates refuge insurance—insurance that pays indemnities for yield losses on refuge due to insect damage—as a tool to increase grower compliance incentives.

We determine actuarially fair insurance premiums, then evaluate the feasibility of private provision of refuge insurance and its impact on grower incentives to comply with refuge requirements. A private market for refuge insurance appears unlikely because our analysis suggests that even a 2 percent load on the actuarially fair premium makes growers unwilling to buy refuge insurance. This load is not sufficient to cover administrative costs and provide a normal economic return. Even actuarially fair refuge insurance increases grower compliance incentives less than 3 percent. This result occurs because the primary benefit of Bt corn is yield enhancement and not risk reduction, but refuge insurance only reduces risk. For refuge insurance to provide significant compliance incentives, conventional insurance products must be restructured to draw premiums from sources other than grower risk premiums.

Key Words: Bt corn; crop insurance; refuge crops; pest-resistant management; European corn borer; yield loss.

ECONOMIC EVALUATION OF BT CORN REFUGE INSURANCE

Introduction

Recent advances in genetic engineering now allow genes to be transferred between species. Applications of this technology to agriculture include the insertion of a gene from the soil bacterium *Bacillus thuringiensis* (Bt) into corn and other crops. Corn with the Bt gene produces proteins that are toxic when consumed by the European corn borer (ECB) and other Lepidopteran insects. Since its commercial introduction in 1996, Bt corn has proven to be an effective new tool for managing the ECB.

The high efficacy of Bt corn has resulted in rapid and widespread adoption. In 1999, an estimated 25 percent of corn acreage in the United States was planted to Bt Corn. Bt corn's high efficacy and rapid adoption continues to foster concerns about the ECB and other insects developing resistance to Bt. If resistance develops, Bt corn will no longer effectively control the ECB. The potential for insects to develop resistance to highly effective and widely used pesticides is well documented, including resistance to Bt (Bauer, 1995; Liu and Tabashnik, 1997; McGaughey and Beeman, 1998; Perez and Shelton, 1997; and Tabashnik 1994). Concerns about resistance to Bt are heightened by the fact that Bt based pesticides are natural and believed to pose fewer environmental and human health risk than synthetic pesticides. If the efficacy of Bt corn declines substantially due to resistance, growers may turn to more hazardous alternatives to achieve sufficient control.

The U.S. Environmental Protection Agency (EPA) has authority over the introduction, use, and registration of plant-pesticides—pesticides produced by a plant due to the introduction of new genetic material. Therefore, the EPA is partially responsible for regulating and registering Bt corn. Through this authority and acting in the public's interest, the EPA has established guidelines for the use of Bt corn to address resistance concerns and preserve its efficacy as a reduced risk pesticide (U.S. EPA, 1998).

Current resistance management guidelines are based on a high-dose refuge strategy. The high-dose refuge strategy requires Bt corn to produce enough toxin to kill all but the most resistant ECB,

and growers to plant refuges of non-Bt corn. Refuge allows Bt susceptible ECB to survive and mate with resistant ECB emerging from the Bt crop. If there is a high enough dose and sufficient refuge, most of the surviving ECB will be susceptible and so will most of their offspring.

The EPA did not originally impose mandatory refuge requirements on most varieties of Bt corn. However, mandatory requirements were introduced for the 2000-growing season. These mandatory requirements obligate Bt corn registrants to ensure that growers plant at least 20 percent refuge corn in areas where cotton is not grown. Supplemental treatments with non-Bt pesticides based on economic thresholds are permitted to control the ECB on refuge in years of high infestation. While the sale of some Bt corn varieties is expressly prohibited in cotton-growing areas, other varieties can be planted provided there is at least 50 percent refuge corn.

Bt corn provides benefits to growers by increasing average yields and potentially decreasing yield variability. However, not all growers will benefit from planting Bt corn, since the technology fee could exceed the value of increased average yields and decreased yield variability. This is particularly true for areas where ECB infestations are infrequent and not severe. In areas where the value of increased average yields and decreased yield variability does exceed the technology fee, growers have a strong incentive to adopt Bt corn.

When Bt corn is more profitable and less risky, growers may be reluctant to bear the financial burden of planting a portion of their acreage to conventional corn. This burden increases as the required refuge, frequency of ECB infestations, and severity of ECB infestation increases. Because Bt corn is visually indistinguishable from conventional corn, it is difficult to monitor whether growers are adhering to refuge requirements. As a result, there are concerns that many growers may plant less refuge than required or ignore refuge requirements entirely. It is clear, however, that failure to plant adequate refuge accelerates the development of ECB resistance to Bt. In fact, the model described in Hurley, Babcock, and Hellmich (1997) suggests that planting only 5 percent refuge, instead of the required 20 percent, reduces by 66 percent the number of generations until resistance develops.

The EPA's concern for a lack of grower compliance is clear in letters sent to registrants specifying the mandatory resistance management guidelines for the 2000-growing season. These letters require registrants to a) submit a detailed compliance program, b) conduct surveys of grower compliance, and c) implement intensified grower education efforts in areas with compli-

ance problems. Concerns for a lack of grower compliance with resistance management guidelines will continue to grow, since new Bt products for other pests are under development. Indeed, in March 2000 Monsanto filed a request for registration of rootworm Bt corn and other companies are expected to follow. Refuge based resistance management plans are likely to be among the conditions for registration of these new transgenic products.

A number of tools have been proposed to encourage grower compliance with refuge recommendations, including grower education, grower contracts, sales incentives, and refuge insurance. Education makes growers more aware of refuge requirements and their purpose, but does not alleviate the burden of planting refuge. Grower contracts legally obligate growers and provide for sanctions when they fail to meet these obligations. The contracts increase the cost of noncompliance, but again do not relieve the burden of refuge. To be effective, sanctions and the likelihood of detecting noncompliant growers must be substantial.

Sales incentives such as seed rebates for refuge corn reduce the cost of compliance by compensating growers, *ex ante*, for ECB losses on refuge areas; however, several moral hazards exist. As a result, monitoring is required to ensure that growers actually plant rebated seed and do so in the proper configuration. Refuge insurance reduces the cost of compliance by compensating growers, *ex post*, for ECB yield losses on refuge. Before a grower receives an indemnity, an adjuster must inspect the refuge for ECB damage, which also provides an opportunity to verify compliance with refuge requirements.

We develop a general model of single peril insurance for insect crop damages to investigate the feasibility of private markets to offer refuge insurance. For the insurance product we investigate, growers pay premiums and receive indemnity payments on refuge damages minus a deductible. To evaluate the feasibility of private marketing, we calculate both the actuarially fair premium for insurance that pays indemnities based on ECB stalk tunneling and the grower willingness to pay for this insurance under a variety of assumptions. To evaluate refuge insurance as a compliance mechanism, we determine how much refuge insurance increases grower incentives to comply with refuge.

We find that the private provision of refuge insurance for Bt corn is unlikely because grower willingness to pay for refuge insurance is only slightly higher than the actuarially fair premium. This occurs because the risk of yield loss due to ECB is small relative to other risks such as

weather. As a result, the risk reduction benefits of refuge insurance are small and growers will be unwilling to pay substantially more than a fair premium. Thus, private insurers will be unable to load the fair premium to cover administrative costs and earn a normal economic return while still offering an attractive product to growers.

We find that an insurance product structured similarly to conventional insurance products does improve incentives for compliance, but only slightly. The primary benefit of Bt corn is yield enhancement, not risk reduction. As a result, growers find little value in the risk reduction benefits of refuge insurance relative to the yield enhancement benefits of Bt corn. Therefore, conventional products must be restructured before insurance will provide stronger compliance incentives.

General Model of Actuarially Fair Pest Damage Insurance

The model of pest damage insurance abstracts from the use of inputs and most sources of uncertainty in crop production to focus on the stochastic factors pertinent for this analysis. For simplicity, we assume conventional pest control with insecticidal sprays is not economical.

Grower returns per acre (p) are

$$\pi = ry (1 - \lambda) - c \quad (1)$$

where r is the nonstochastic crop price, y is pest free yield, l is the proportion of yield loss due to pest damage, and c is the nonstochastic cost of production. The uncertainty of pest free yield captures the randomness in crop yield due to factors other than damage from the pest of concern, such as weather variability, input application errors, and stochastic availability of applied inputs, as well as other pests and pathogens. As a result, the pest free yield is unconditionally distributed according to the density $b(y)$.

Following Lichtenberg and Zilberman (1986), damage is modeled as a separate stochastic relationship. The proportion of yield loss due to pest damage cannot be directly observed under ordinary crop production conditions, but must be determined by observing s , an *ex post* damage assessment signal. Unless a grower experimentally plants treated and untreated plots with sufficient replications to ensure that observed differences are due to a difference in treatments and not other uncontrolled random factors, the actual loss due to pest damage cannot be accurately assessed. However, entomologists, weed scientists, and plant pathologists perform numerous

experiments in order to develop useful *ex post* damage assessment signals for use in evaluating pest control techniques. Using such a signal, growers can estimate yield losses due to pest damage under normal crop production conditions without performing replicated plot experiments. Examples specific to important insects in midwestern corn production include tunneling by stalk boring insects such as ECB, as well as lodging and root ratings to assess damage by corn rootworm (Lynch et al., 1980; Gray and Steffey, 1998; Spike and Tollefson, 1989; 1991).

The proportion of yield loss due to pest damage (l) is not perfectly correlated with the observed signal s . Rather the relationship between s and l is stochastic and the distribution of l conditional on s must be estimated using experimental or field data. In the model specified here, l is distributed according to the conditional density $h(\lambda | s)$.

For nonmobile pests such as weeds, the signal s is often some measure of population density (p), so that $s = p$. However, for insects the damage assessment signal s should be some measure other than p , since often insects can feed on plants (leaving feeding scars), then move elsewhere. However, damage and its assessment with a signal (usually derived from feeding scars) must depend on an underlying pest population. As a result, the signal s is conditionally distributed on the pest population p . And in the model specified here, s is distributed according to the conditional density $w(s | p)$. To recover this stochastic relationship between s and p again requires experimental or field data.

Lastly, the pest population must be modeled. Stochastic dynamic population models can be used to estimate a density function for the pest population conditional on pertinent factors such as grower management practices or observable weather variables (Mitchell, 1999). However, an alternative is to estimate an unconditional density $v(p)$ for the pest population using field data collected over several years and/or locations.

To summarize, growers receive per-acre returns as described by equation (1).

- The pest free yield (y) is unconditionally distributed according to the density $b(y)$.
- The yield loss per acre due to pest damage (λ) is conditionally distributed according to the density $h(\lambda | s)$.
- The *ex post* damage assessment signal (s) is conditionally distributed according to the density $w(s | p)$.
- The pest population (p) is unconditionally distributed according to the density $v(p)$.

Complete insurance is a useful base case for analysis. Given this specification, complete insurance pays an indemnity equal to the dollar value of the expected loss due to pest damage conditional on the *ex post* damage assessment signal s . Denote this indemnity $L(s)$ and assume that y and l are independent, so that

$$L(s) = r \int_y y b(y) dy \int_\lambda \lambda h(\lambda | s) d\lambda \cdot \quad (2)$$

The actuarially fair premium (M) is the expected value of this indemnity, which requires integrating $L(s)$ across s then p , since s is distributed conditional on p :

$$M = r \int_p \int_s L(s) w(s | p) v(p) ds dp \cdot \quad (3)$$

Expected per acre returns do not change with this insurance, but the variance of returns will decrease as long as the indemnity $L(s)$ —the value of the expected losses conditional on the observed damage assessment signal s —is negatively correlated with returns p .

Empirical Model of European Corn Borer Insurance

Pest Free Yield: $y \sim b(y)$

This analysis assumes pest free yield is distributed according to a beta density with four parameters—the minimum and maximum yields, plus two shape parameters a and w . Parameter values are those used to determine county multiple-peril crop insurance (MPCI) premiums for dryland corn in Boone County, Iowa. Minimum and maximum yields are 0 and 212 bushels, while $a = 3.26$ and $w = 1.61$. These parameters imply an average yield of 141.9 bushels per acre, with a standard deviation of 41.2 bushels.

These parameters were estimated without correcting for yield losses due to ECB pressure. As a result, the actual pest free yield is probably higher and has a lower variance. While better data on pest free yields is forthcoming with the widespread adoption of Bt corn, we currently rely on an extensive sensitivity analysis to demonstrate that this caveat does not change the conclusions of the report. In addition, this analysis assumes pest free yield is uncorrelated with the ECB population (and thus observed ECB damage). Some correlation between the ECB population and pest free corn yields is probable, but likely to be small. Both yields and ECB populations are strongly influenced by weather. However, yields depend more on cumulative

weather effects throughout a season, while ECB populations are influenced more by weather events occurring during critical stages of their life cycle.

Larval Population: $p \sim v(p)$

Longitudinal data for average state ECB populations (4th or 5th instar ECB per plant) were available for three states—Illinois (1943–84, 1987–96), Minnesota (1963–98) and Wisconsin (1963–98). Examining histograms and time trends for these data indicated a rightward skew and potential upward drift in the mean and variance over time for Minnesota and Wisconsin. Since the pest population must be positive, various specifications of a lognormal and gamma distribution with and without a time trend were fitted to the data using maximum likelihood. Time trends were statistically insignificant at the 5 percent level and were removed from the model. The lognormal distribution produced a higher maximized value for the log-likelihood function than the gamma distribution for the same number of estimated parameters. No significant autocorrelation was identified in the prediction errors for the lognormal distribution based on the Durbin-Watson test using a 5 percent level of significance.

Based on this analysis, the lognormal density is used for the unconditional distribution of second generation 4th and 5th instar ECB larvae population per plant:

$$v(p) = \frac{1}{p\sqrt{2\pi\sigma^2}} \exp\left(\frac{-(\log p - \mu)^2}{2\sigma^2}\right).$$

Table 1 reports parameter estimates for the distribution for each of the three states. Parameter estimates imply a mean per plant ECB population of 1.20, 0.81, and 0.55 for Illinois, Minnesota, and Wisconsin, with a coefficient of variation of 1.06, 0.94, and 0.71.

Damage Assessment Signal: $w(s|p)$

In this analysis, measured tunneling by ECB larvae in corn stalks is used as the damage assessment signal. Field-level data collected from Bt field trials conducted in 1997 by collaborators in 10 states (Iowa, Illinois, Kansas, Maryland, Minnesota, Missouri, Nebraska, Ohio, South Dakota, and Wisconsin) were obtained from Monsanto. The average number of larvae (4th and 5th instars per plant) and average tunneling (cm) were collected for 311 Bt fields and 234 non-Bt

fields for a total of 545 observations. Most of the fields (70.8 percent) were from sites in Iowa, Illinois, and Nebraska. Figure 1 plots the observed field average tunneling against the observed field average ECB larvae for the Bt and non-Bt fields separately. As expected, Bt corn provides very effective control of ECB. As a result, only data from non-Bt fields are used for estimation.

Table 1. Parameter estimates and associated statistics for $v(p)$, the unconditional distribution of 4th and 5th instar ECB per plant

State	Parameter	Estimate	Standard Error*	t statistic	p value
Illinois	μ	-0.024	0.089	-0.274	0.784
Illinois	σ	0.64	0.063	10.2	0.000
Minnesota	μ	-0.48	0.137	-3.54	0.000
Minnesota	σ	0.77	0.097	8.00	0.000
Wisconsin	μ	-0.89	0.148	-6.02	0.000
Wisconsin	σ	0.84	0.105	8.00	0.000

*Standard Errors computed from analytic second derivatives (Newton's method).

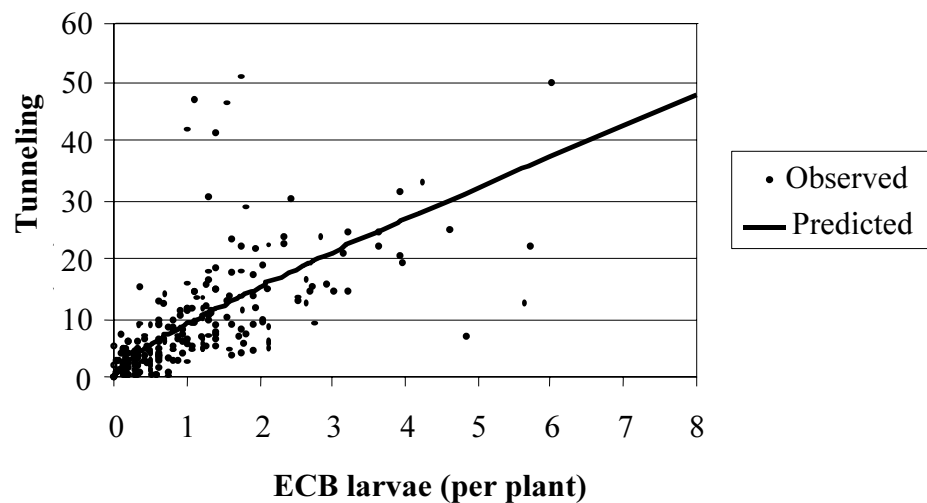


Figure 1. Observed and predicted field average tunneling (cm) versus field average ECB 4th and 5th instar population per plant.

Field average tunneling must be strictly non-negative, so densities such as the lognormal or gamma are reasonable. However, examining histograms of tunneling at different numbers of ECB indicated that a flexible density function such as the gamma is appropriate, since as the larval population increased, histograms went from L-shaped to unimodal curves with rightward

skewing. The data also indicate that as the number of ECB increases, the standard deviation of tunneling increases in an approximately linear manner. Figure 1 indicates that as the number of ECB increases, average tunneling increases less than proportionally. To estimate the distribution of tunneling conditional on ECB larvae, various maximum likelihood models were evaluated assuming that tunneling followed a gamma distribution. To capture the effect of the ECB population, the estimation imposed a linear relationship between the standard deviation of tunneling and ECB larvae. Using this linear standard deviation, various non-linear models were evaluated for mean tunneling as a function of observed ECB larvae, including quadratic, negative exponential, square root and hyperbolic. A zero intercept was imposed for each, since the intercept parameter was insignificant.

The square root model performed the best. The mean for the quadratic model began to decrease with higher ECB populations, the negative exponential never converged and the hyperbolic predicted unrealistically small mean tunneling at high ECB populations. The resulting

density function for the square root model is $w(s | p) = \frac{s^{\theta-1} \exp(-s / \beta)}{\phi^\theta \Gamma(\theta)}$, where q and f , the pa-

rameters of the gamma distribution, are $\theta = \frac{v^2 p}{(\alpha + \beta p)^2}$ and $\phi = \frac{(\alpha + \beta p)^2}{v \sqrt{p}}$, and a , b , and n are

parameters to estimate. The mean of the gamma density is $f q$ and the standard deviation is $\phi \sqrt{\theta}$,

so that mean tunneling is $\theta \phi = v \sqrt{p}$ and the standard deviation of tunneling is $\phi \sqrt{\theta} = \alpha + \beta p$.

Figure 1 plots this estimated mean with the observed data, while Table 2 reports maximum likelihood parameter estimates for a , b , and n .

Table 2. Parameter estimates and associated statistics for $w(s | p)$, the distribution of tunneling (cm) conditional on second generation ECB larvae population

Parameter	Estimate	Standard Error*	t statistic	p value
α	3.104	0.4774	6.502	0.000
β	2.460	0.4544	5.413	0.000
v	9.258	0.4940	20.602	0.000

* Standard Errors computed from analytic second derivatives (Newton's method).

Proportion of Yield Lost: $\lambda \sim h(\lambda | s)$.

Data from field experiments conducted in 1995 near Ames, Iowa, were used to estimate a stochastic model for yield loss conditional on the measured stalk tunneling. Eight treatments were applied in six blocks. A non-Bt hybrid (B73xMo17) was exposed to (1) natural ECB infestation without any control measure, (2) natural ECB infestation treated with Pounce insecticide, (3) natural ECB infestation treated with Dipel insecticide (4) artificial ECB 1st instar infestation. Two different Monsanto Bt events (MON 810 and MON 802) in the same hybrid were each exposed to (1) natural ECB infestation and (2) artificial ECB 1st instar infestation.

Yield data were collected for each treatment within each block for 48 yield observations (six blocks with eight treatments each). In the six blocks, the four Bt corn treatments showed almost no ECB tunneling, even under extraordinarily high artificial ECB larval populations. The average yield of these four treatments in each block is used as the estimate of pest free yield for that block. For each treatment in each block, the ratio of the block pest free yield minus the observed treatment yield to the block pest free yield gives 48 observations of l , the proportion of yield lost.

At the end of the season 15 plants were cut and split and stalk tunneling (cm) measured for each treatment in a block. Tunneling was not observed in all 720 plants analyzed. Of the 394 plants with no observed tunneling, 338 (86 percent) were Bt plants and 43 (11 percent) were treated with Pounce or Dipel, and 13 (3 percent) were natural infestations. All artificially infested plants had positive tunneling. For the 326 plants with tunneling, the average was 8.9 cm with a standard deviation of 8.3 cm. Calculating the average tunneling for each treatment in each block (including all zeros) gives 48 observations of average tunneling, for the damage assessment signal s .

Figure 2 plots observed yield loss versus average tunneling. The correlation coefficient is 0.57, and Figure 2 indicates a general positive relationship. A nonlinear damage model that asymptotically approaches 100 percent loss as tunneling increases seems appropriate. A negative exponential model is used to restrict losses to be strictly less than 100 percent:

$\lambda = 1 - \exp(-ks)$, where the parameter k determines how rapidly losses rise to 100 percent.

Transforming the model for linear estimation yields $\ln(1 - \lambda) = -ks + \eta\varepsilon$, where h is the standard

deviation of transformed losses around the predicted mean and $e \sim N(0,1)$ is the random error. Table 3 reports maximum likelihood estimates for the parameters k and h , while Figure 2 illustrates the fit provided by the model.

Given this model, no convenient expression for the conditional distribution of yield loss $\lambda \sim h(\lambda | s)$ exists; however, $(1 - l)$, the proportion of yield remaining after ECB losses, follows the lognormal density with mean $m\sqrt{\exp(\eta^2) - 1}$ and standard deviation $m\sqrt{\exp(\eta^2) - 1}$.

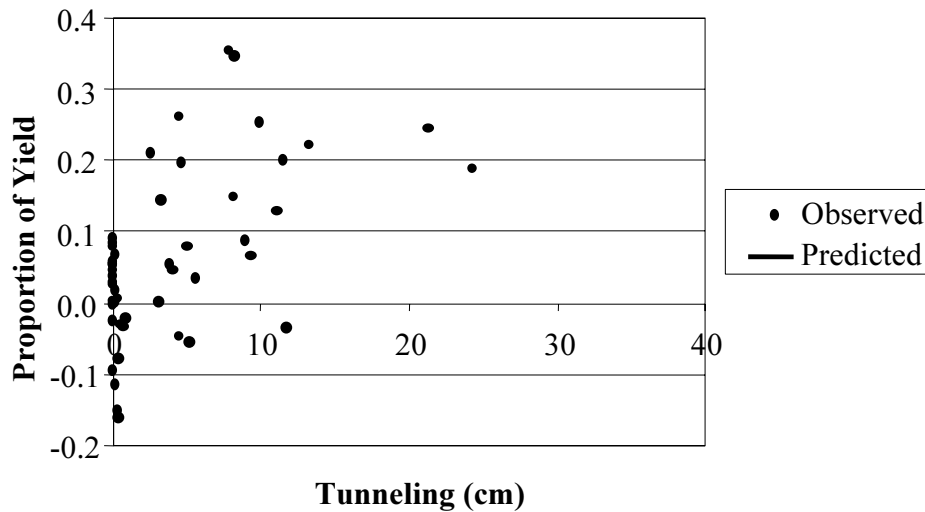


Figure 2. Observed and predicted proportion of yield lost versus average tunneling (cm).

Table 3. Parameter estimates and associated statistics for $h(\lambda | s)$, the distribution of the proportion of yield lost conditional on tunneling (cm)

Parameter	Estimate	Standard Error*	t statistic	p value
κ	0.0153	0.0112	9.7980	0.000
η	0.1102	0.0023	6.6083	0.000

* Standard Errors computed from analytic second derivatives (Newton’s method).

As a result, expected yield loss conditional on the tunneling signal s is $m\sqrt{\exp(\kappa s - 0.5\eta^2)}$, while the conditional standard deviation is the product of this conditional mean and $\sqrt{\exp(\eta^2) - 1}$. Figure 2 plots the conditional mean. The standard deviation of yield loss is not plotted, but it increases with tunneling in a manner similar to the conditional mean, but at a slower rate and with a smaller maximum.

Though this damage model prevents yield losses in excess of 100 percent, it does permit losses below 0 percent (i.e. gains) at small levels of tunneling. The expected proportion lost when $s = 0$ is $s = 0$ is and does not cross the axis until $s = \frac{\eta^2}{2\kappa}$. Using parameter values reported in Table 3, this implies that at zero tunneling yield loss is -0.61 percent and expected loss does not become positive until $s = 0.4$ cm. Therefore, the analysis imposes a yield drag on Bt corn of 0.61 percent. The results reported below assume that Bt corn completely controls ECB, so pest free yield is used. The damage model is used to adjust the pest free yields for refuge corn.

The data exhibit substantial variation in yield loss for the same observed tunneling because other factors in addition to tunneling contribute to deviations from pest free yields (Bode and Calvin, 1990; Calvin et al., 1988; Jarvis et al., 1961). Other researchers report similar low correlation between tunneling and yield loss (Berry and Campbell, 1978; Lynch et al., 1980), indicating that this variation cannot be avoided when using tunneling as a damage assessment signal. The result is typical for pest damage assessment signals because of the substantial natural variation in agricultural ecosystems and is an empirical reality that any pest insurance program faces.

Evaluation of ECB Insurance

Actuarially Fair Premiums

The general indemnity represented by equation (2) does not include a deductible as is common for most types of insurance. For ECB refuge insurance, a deductible equal to the technology fee growers pay to purchase Bt seedcorn is reasonable, since it is the minimum value of damages refuge corn must suffer before it is less profitable than Bt corn. With a deductible the indemnity becomes

$$I(s) = \text{Max}\{L(s) - D, 0\}, \quad (4)$$

where $L(s)$, the dollar value of the expected loss given the observed tunneling s , is defined by equation (2), and D is the deductible. Again the actuarially fair premium M is the expected value of this indemnity:

$$M = \int_p \int_s I(s) w(s | p) v(p) ds dp \cdot \quad (5)$$

The integral in equation (5) is analytically intractable for the density functions derived using the experimental and field data described above. Monte Carlo integration can be used to solve the

integral numerically by drawing several random variates from the specified probability densities, substituting them into equation (5), and then calculating the average. This Monte Carlo integration is an unbiased estimate of the integral and the standard error of the estimate decreases as the number of random variates increases.

Table 4 reports actuarially fair insurance premiums over a range of assumptions for the ECB population mean and coefficient of variation, using a corn price of \$2.20 per bushel and a \$10 deductible (equal to the typical technology fee). Experimentation indicated that 20,000 random variates for each probability density function were sufficient for premium estimates to stabilize.

Table 4. Actuarially fair premiums (\$/ac) for ECB refuge insurance over a range of assumptions for the ECB population mean and coefficient of variation

Mean	Coefficient of Variation							
	0.50	0.71	0.75	0.94	1.00	1.06	1.25	1.50
0.50	\$18.06	\$17.84	\$17.79	\$17.53	\$17.44	\$17.35	\$17.05	\$16.66
0.55	\$19.30	\$19.04	\$18.99	\$18.69	\$18.59	\$18.49 ^c	\$18.15	\$17.71
0.75	\$23.73	\$23.33	\$23.25	\$22.81	\$22.66	\$22.52	\$22.05	\$21.45
0.81	\$24.89	\$24.46	\$24.37	\$23.89 ^b	\$23.73	\$23.58	\$23.07	\$22.43
1.00	\$28.54	\$28.00	\$27.89	\$27.30	\$27.10	\$26.91	\$26.28	\$25.50
1.20	\$31.91	\$31.28 ^a	\$31.15	\$30.45	\$30.22	\$30.00	\$29.26	\$28.34
1.25	\$32.73	\$32.07	\$31.94	\$31.21	\$30.97	\$30.74	\$29.98	\$29.03
1.50	\$36.46	\$35.69	\$35.54	\$34.70	\$34.42	\$34.15	\$33.27	\$32.17

^a Illinois state average larval population model.

^b Minnesota state average larval population model.

^c Wisconsin state average larval population model.

The first result apparent in Table 4 is the relatively high cost of actuarially fair premiums for ECB insurance. State average cash expenses typically range from \$170 to \$190 an acre for corn production in the Midwest. The actuarially fair premiums range from \$16.66 to \$36.46 representing about a 9 percent to 21 percent increase in cash expenses. These large premiums result from the large predicted yield losses for ECB damage—13.0 percent, 10.5 percent, and 8.5 percent for Illinois, Minnesota, and Wisconsin respectively. Calvin (1996) reports an estimate of 6.4 percent for the average annual U.S. yield loss due to ECB, while Bullock and Nitsi (1999) estimate an average annual yield loss 3.5 percent using the data from Illinois, Minnesota, and Wisconsin. The origin of these damage estimates is field experiments conducted prior to the advent of Bt corn. With the advent of Bt corn and the data from Bt corn field trials, some entomologists are ques-

tioning whether previous estimates are too low. In addition, the field trial data used to estimate the damage model are based on the B73xMo17 hybrid, which is known to be susceptible to ECB damage that causes yield loss. Also, including data from extremely high artificial ECB infestation experiments may have biased the damage model estimation upward. Whether previous estimates are too low or model estimates are too high is an empirical question requiring further experimentation.

Gross revenue also affects the actuarially fair premium. Because gross revenue is a linear function of price and the pest free yield, increasing the price while holding the mean and variance of the pest free yield constant has the same impact as increasing the average pest free yield while holding the price and coefficient of variation of pest free yield constant. Thus the impact of average gross revenue on the fair premium can be evaluated by changing the price of corn or the average pest free yield. Table 5 reports the actuarially fair premium for a range of corn prices for Illinois, Minnesota, and Wisconsin larval densities. As gross revenue increases, the actuarially fair premium increases, though not proportionally. As the price increases, not only does gross revenue and the value of losses increase, but it also becomes more likely that losses exceed the deductible and trigger a payment. With a proportionally higher indemnity being paid and indemnities being paid more often, the expected indemnity increases by more than gross revenues.

Table 5. Sensitivity of actuarially fair premium to the price of corn

Price of Corn (\$/Bushel)	Illinois	Minnesota	Wisconsin
\$1.80	\$23.99	\$18.11	\$13.86
\$1.90	\$25.81	\$19.55	\$15.01
\$2.00	\$27.63	\$20.99	\$16.16
\$2.10	\$29.45	\$22.44	\$17.32
\$2.20	\$31.28	\$23.89	\$18.49
\$2.30	\$33.11	\$25.34	\$19.66
\$2.40	\$34.94	\$26.80	\$20.83
\$2.50	\$36.77	\$28.27	\$22.01
\$2.60	\$38.61	\$29.73	\$23.19
\$2.70	\$40.44	\$31.20	\$24.37
\$2.80	\$42.28	\$32.67	\$25.56

Because the estimated average annual yield loss exceeds previous estimates in the literature, the impact of reducing the average annual yield loss on the fair premium is investigated while holding the coefficient of variation for yield loss constant. Table 6 reports results for Illinois,

Minnesota, and Wisconsin larval densities. As expected, the actuarially fair premium decreases with average damages. Again, the relationship is not proportional since damages increase at a decreasing rate and the deductible reduces the probability that indemnities are paid as average damages decrease. As a result, the percentage decrease in damages is smaller than the percentage decrease in the actuarially fair premium. With average damages closer to estimates found in previous literature, the actuarially fair premium ranges between \$7 and \$12 per acre, or about 4 percent to 7 percent of typical cash expenses.

Table 6. Actuarially fair premiums over a range of average damages with a constant coefficient of variation of damages

Illinois		Minnesota		Wisconsin	
Average Damage	Fair Premium	Average Damage	Fair Premium	Average Damage	Fair Premium
13.0%	\$31.28	10.5%	\$23.89	8.5%	\$18.49
12.4%	\$29.42	10.0%	\$22.39	8.1%	\$17.26
11.8%	\$27.54	9.5%	\$20.87	7.7%	\$16.03
11.2%	\$25.65	9.0%	\$19.36	7.2%	\$14.80
10.5%	\$23.75	8.4%	\$17.83	6.8%	\$13.56
9.9%	\$21.83	7.9%	\$16.30	6.4%	\$12.33
9.3%	\$19.90	7.4%	\$14.77	5.9%	\$11.10
8.6%	\$17.96	6.8%	\$13.25	5.5%	\$9.88
8.0%	\$16.02	6.3%	\$11.73	5.1%	\$8.67
7.3%	\$14.08	5.8%	\$10.21	4.6%	\$7.48

Feasibility of Private Provision

Private insurance companies load actuarially fair premiums in order to cover administrative costs and earn a normal rate of return. For a private insurance market to function, the load plus the actuarially fair premium must be less than grower risk premiums, or growers have no incentive to purchase the insurance. This analysis assumes grower preferences exhibit constant absolute risk aversion, then solves for the premium that equates the expected utility of planting Bt corn and refuge with and without insurance. This premium reflects the maximum willingness to pay for actuarially fair refuge insurance. The difference between this and the actuarially fair premium is the maximum possible load that can be added and still leave growers some incentive to purchase ECB insurance for their refuge. Following Babcock et al. (1993) the coefficient of

absolute risk aversion is set at 0.00456, corresponding to a risk premium equal to approximately 20 percent of the standard deviation of profit and indicative of a fairly risk averse grower. Table 7 reports the resulting maximum possible load over a range of assumptions for the ECB population mean and coefficient of variation.

Table 7. Maximum possible load on actuarially fair premium for a risk averse^a grower over a range of ECB population assumptions

Mean	Coefficient of Variation							
	0.50	0.71	0.75	0.94	1.00	1.06	1.25	1.50
0.50	\$0.15	\$0.17	\$0.17	\$0.18	\$0.19	\$0.19	\$0.20	\$0.22
0.55	\$0.16	\$0.18	\$0.18	\$0.19	\$0.20	\$0.20 ^d	\$0.22	\$0.23
0.75	\$0.19	\$0.21	\$0.22	\$0.24	\$0.24	\$0.25	\$0.27	\$0.29
0.81	\$0.20	\$0.22	\$0.23	\$0.25 ^c	\$0.26	\$0.26	\$0.28	\$0.31
1.00	\$0.24	\$0.26	\$0.27	\$0.29	\$0.30	\$0.31	\$0.34	\$0.36
1.20	\$0.27	\$0.31 ^b	\$0.31	\$0.34	\$0.35	\$0.36	\$0.39	\$0.42
1.25	\$0.29	\$0.32	\$0.32	\$0.36	\$0.37	\$0.37	\$0.40	\$0.43
1.50	\$0.34	\$0.38	\$0.38	\$0.42	\$0.43	\$0.44	\$0.47	\$0.50

^a Coefficient of absolute risk aversion equal to 0.00456, or a risk premium approximately equal to 20 percent of the standard deviation of profit.

^b Illinois state average larval population model.

^c Minnesota state average larval population model.

^d Wisconsin state average larval population model.

The values in Table 7 are extremely small relative to the fair premiums (less than 2 percent) and the values are far too small to cover the costs of providing refuge insurance. Given this result, a private market for refuge insurance does not seem feasible. Grower willingness to pay for actuarially fair insurance is not much greater than the fair premium primarily because of the small risk of ECB losses relative to other factors such as weather. For example, assuming a cash production cost of \$180 and using Illinois larval population parameters, a grower planting Bt corn with 20 percent refuge has an average profit of \$116.01 per acre with a standard deviation of \$88.43 per acre. If the pest free yield is held constant at its mean of 141.9 bushels, so that the only uncertainty in profit is due to stochastic ECB losses, average profit remains essentially unchanged but its standard deviation falls to \$6.10.

More risk averse growers have a greater willingness to pay for refuge insurance. Table 8 reports the maximum possible load as the coefficient of absolute risk aversion increases from 0.00111 to 0.00710, equivalent to the risk premium increasing from 5 percent to 30 percent of

the standard deviation of profit. Again, the maximum possible load is small even with extreme risk aversion, which further supports the conclusion that refuge insurance is not feasible for private insurance markets.

Table 8. Effect of the coefficient of absolute risk aversion on the maximum possible load

Risk Aversion ^a	Risk Premium ^b	Illinois	Minnesota	Wisconsin
0.00111	5%	\$0.09	\$0.07	\$0.06
0.00223	10%	\$0.17	\$0.14	\$0.11
0.00338	15%	\$0.24	\$0.20	\$0.16
0.00456	20%	\$0.31	\$0.25	\$0.20
0.00579	25%	\$0.36	\$0.30	\$0.24
0.00710	30%	\$0.42	\$0.34	\$0.28

^a Coefficient of absolute risk aversion.

^b As percent of standard deviation of profit.

The sensitivity of this result was explored further by determining the maximum possible load over a wide range of values for key parameters. The impact of gross revenue was determined by varying the price of corn from \$1.80 to \$2.80. Average damages (holding the coefficient of variation constant) was varied from 13 percent to 4.6 percent, while the coefficient of variation of damage (holding the mean constant) was varied from 32 percent to 0 percent. The deductible was varied from \$20 to \$0. The results of this sensitivity analysis are not reported, but the maximum possible load never exceeded 2 percent of the actuarially fair premium, indicating the robustness of this result to model assumptions.

Impact of ECB Insurance on Refuge Compliance Incentives

Growers have no economic incentive to voluntarily comply with refuge requirements because refuge corn is less productive on average and more risky. Actuarially fair refuge insurance by definition does not change average returns from refuge. However, the insurance does reduce the riskiness of returns from refuge corn, removing some of the disincentive to comply with refuge requirements by reducing the cost of compliance. Even with actuarially fair refuge insurance, growers have no incentive to voluntarily comply with refuge requirements, because it is not likely that growers value of the risk reduction provided by insurance more than they value the average yield increase provided by Bt corn. However, because refuge insurance reduces the cost

of compliance for risk averse growers, refuge insurance does reduce the incentive for growers to violate refuge requirements. To evaluate how much refuge insurance reduces the cost of compliance, we determine the minimum amount of compensation a grower needs in order to voluntarily plant refuge with and without insurance.

Table 9 shows the percentage reduction in compensation required for growers to voluntarily adopt refuge requirements when refuge insurance is made available, which is a useful measure of the increase in grower incentives to comply with refuge requirements. Because refuge insurance reduces only a minor source of the risk faced by growers, refuge insurance only slightly increases (less than 2 percent) grower incentives to comply with refuge requirements. To provide stronger compliance incentives, refuge insurance must also increase the average return from refuge. However, in the context of insurance product modeled here, this requires charging less than the actuarially fair premium and thus is not a feasible solution for private insurance providers. Conventional insurance products must be restructured to draw premiums from sources other than the grower risk premium if these products are to increase average returns on refuge and compliance incentives more substantially.

Table 9. Percentage increase in grower incentives to voluntarily comply with refuge requirements when actuarially fair insurance is purchased

Mean	Coefficient of Variation							
	0.50	0.71	0.75	0.94	1.00	1.06	1.25	1.50
0.50	1.1	1.2	1.3	1.4	1.5	1.5	1.7	1.9
0.55	1.1	1.2	1.2	1.3	1.4	1.5 ^c	1.6	1.9
0.75	1.0	1.1	1.2	1.3	1.4	1.4	1.6	1.8
0.81	1.0	1.1	1.1	1.3 ^b	1.3	1.4	1.5	1.8
1.00	1.0	1.1	1.2	1.3	1.4	1.4	1.6	1.8
1.20	1.0	1.2 ^a	1.2	1.4	1.4	1.5	1.6	1.8
1.25	1.0	1.2	1.2	1.4	1.4	1.5	1.6	1.8
1.50	1.1	1.2	1.3	1.4	1.5	1.5	1.7	1.9

^a Illinois state average larval population model.

^b Minnesota state average larval population model.

^c Wisconsin state average larval population model.

Again, we explored the sensitivity of this result to model assumptions by varying key parameters over the same ranges as with the previous sensitivity analysis. These parameters included the price of corn, average damage, the coefficient of variation of damage, the deductible, and grower

risk aversion. The results of this analysis are not reported, but in no case did refuge insurance increase grower incentives to comply with refuge requirements by more than 3 percent.

Conclusion

Bt crops offer growers a powerful new tool for controlling damaging insects and reducing reliance on more hazardous conventional pesticides. The evolution of insect resistance to Bt poses a serious threat to the long-term efficacy of Bt crops. The EPA has imposed mandatory guidelines for the use of Bt crops in order to reduce the risk of insect resistance and preserve the long-term efficacy of Bt as a reduced risk pesticide. These mandatory guidelines require growers to plant a proportion of their acreage to a refuge crop in order to slow the development of insect resistance.

Growers have no economic incentive to voluntarily comply with EPA guidelines because refuge crops are less productive on average and are more risky. Since monitoring and enforcing grower compliance is costly, the EPA is interested in identifying other methods to encourage growers to plant refuge. One option being discussed is refuge insurance—insurance that pays indemnities for yield losses on refuge due to insect damage. Refuge insurance reduces the riskiness of returns from refuge and growers value this risk reduction. As a result, refuge insurance can increase compliance incentives by increasing the value of refuge to growers.

We develop a general model of pest damage insurance, then estimate the necessary parametric density functions to create an empirical model of ECB insurance. Using this model, we determine the actuarially fair insurance premiums for a wide range of model parameters. The feasibility of private provision of this ECB insurance for Bt corn refuge is evaluated, as well as the impact of this refuge insurance on grower incentives to comply with refuge requirements.

We find it unlikely that growers will buy refuge insurance offered by private insurance markets. The overall reduction in risk provided by refuge insurance is small relative to other sources of risk that growers face. As a result, growers are only willing to pay slightly more than an actuarially fair premium for refuge insurance. Our estimates suggest that if insurance companies charge even 2 percent more than the actuarially fair premium, growers would be unwilling to

buy refuge insurance. A 2 percent load on the actuarially fair premium is not sufficient to cover administrative costs and provide a normal economic return.

We find that actuarially fair refuge insurance increases grower incentives to comply with refuge requirements by less than 3 percent. This occurs because the primary benefit of Bt corn is yield enhancement and not risk reduction. Since refuge insurance only reduces risk, it can provide only a small increase in grower incentives to comply with refuge requirements.

The conventional structure of the insurance product explored in this report shows little promise. Insurance companies will be unable to offer a product at premiums that are attractive to growers. Even if premiums were actuarially fair, few growers would find the insurance valuable. For refuge insurance to provide significant incentives for growers to comply with refuge requirements, conventional insurance products must be restructured to draw premiums from sources other than the grower risk premium. A new insurance product that derives premiums from other sources could be feasible provided it increased the average return to refuge acreage.

Endnotes

¹This assumption is reasonable for refuge corn and ECB control in most of the Midwest (Demetra et al, 1999). The model can be further generalized for circumstances where it is not.

²Data from Bullock and Nitsi (1999).

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