What Is the Value of Bt Corn?

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May 14, 2001

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Paper prepared for presentation as a Select Paper at the American Agricultural Economics Association Annual Meetings in Chicago, IL, August 5-8, 2001.

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Abstract

A common perception is that the value of Bt corn arises from two components—Bt corn increases expected profit and reduces profit variability. This perception encourages farmers and the policy makers to add a risk benefit to estimates of the value of Bt corn to account for the variability reduction. However, a conceptual model generates a useful decomposition of the value of Bt corn and a condition determining the impact of Bt corn on profit variability. An empirical model finds that Bt corn increases profit variability and thus decreases the value of Bt corn by 10-25% depending on risk preferences.

Key Words: Bt Corn, European corn borer, risk reduction, conditional distribution, Monte Carlo integration.

Introduction

Bt corn is genetically engineered to contain one of many proteins found in the soil bacterium *Bacillus thuringiensis* (Bt). The protein is toxic when consumed by lepidopterous insects such as the European corn borer (ECB), which has been estimated to cost U.S. farmers over $1 billion annually in yield losses and control costs (Mason et al.). Most varieties of Bt corn offer nearly one hundred percent full season control of the ECB, which has resulted in rapid and widespread adoption. Between 1996 and 1999, the percentage of U.S. corn acreage planted to Bt varieties increased from less than one to more than 20 (USDA/NASS). In 2000, adoption of Bt corn decreased due to various market and biological factors— market opposition to genetically engineered crops increased uncertainty, and low commodity prices and less severe ECB infestations lowered the value of pest control. Yet, it is still expected to represent almost 20 percent of all corn acreage in 2001.

Farmers have a substantial interest in understanding the value of Bt corn in order to make better pest control decisions in an environment of low commodity prices and increased marketing uncertainty. The U.S. Environmental Protection Agency (EPA) is also interested in understanding the value of Bt corn to farmers to help facilitate its quantitative benefit and risk assessment when reassessing the conditional registrations of Bt corn. However, studies to help guide farmers and the EPA have been limited. Fernandez-Cornejo and McBride use farm level survey data to estimate the *ex post* value of Bt corn to farmers in 1997 and 1998. The analysis serves as useful retrospective on the control benefits farmers enjoyed from Bt corn in its initial years of adoption, but does not provide useful estimates of the expected value of Bt corn since ECB populations vary substantially over time. It also does not consider the benefits of reduced risk that Bt corn may offer. Hyde et al. explores the expected value of Bt corn for a typical Indiana farm using estimates of the frequency and severity of ECB infestations and yield losses from extension entomologists. The analysis provides useful estimates of the expected value of Bt corn including the value of yield protection and risk reduction. The analysis is however limited in scope and relies heavily on expert opinions, opinions that seem to be changing markedly with additional experience planting Bt corn.

The most tangible benefit of planting Bt corn is yield protection in years of significant ECB infestation. But the variability of ECB infestations means that the value of yield protection may not always be enough to cover the technology fee paid to plant Bt corn (Gianessi and Carpenter). Since farmers cannot accurately predict the years when Bt corn will pay for itself, many extension entomologist and economists frame the decision to purchase Bt corn as a decision to purchase insurance. Treating Bt corn as insurance implies substantial risk management benefits exist in addition to value of higher expected yields and that risk averse farmers should be willing to pay more for Bt corn than just the value of the expected yield increase.

The insurance analogy is a powerful argument for buying Bt corn even though it may not always prove profitable. But, how accurate is this analogy? Should farmers attribute substantial value to Bt corn because it helps them effectively manage yield risk? Bt corn may reduce yield stability and in fact offer a substantial insurance benefit to farmers (see Hyde et al.), but this result is not assured. Horowitz and Lichtenberg (1994) argue in their theoretical analysis that increased pest control does not necessarily imply reduced risk. Their empirical analysis supports this result, though Smith and Goodwin point out specification errors that call their empirical analysis into question. If losses due to pests are higher in good years and lower in bad years, pests may actually serve to reduce risk by increasing yield stability. While pests unequivocally reduce yields, if the extra cost of planting Bt corn just equals the value of higher expected yield, any decrease in the stability of yield could actually make risk averse farmers worse off.

Whether Bt corn is risk increasing or risk reducing is an empirical question that depends on the relationship between yield and pest variability. The purpose of this paper is to evaluate the value of Bt corn based on the expected frequency and severity of ECB infestations and to explore the perception that Bt corn offers substantial insurance benefits. Instead of relying on expert opinion, we use a variety of field data to econometrically characterize yield protection offered by Bt corn and the severity and frequency of ECB infestations.

The results indicate that Bt corn offers substantial value to farmers in much of the Corn Belt, particularly in areas where adoption rates are relatively high. Decomposing the value of Bt corn into the value of yield protection and the risk management benefit, not surprisingly we find that the majority of the value stems from increased yield protection. However, our analysis suggests Bt corn tends to decrease yield stability not increase it. As a result, increased risk reduces the value of Bt corn by 10-25% depending on the frequency and severity of ECB infestations and farmer risk preferences.

Valuing Bt Corn: A Conceptual Framework

Let π be a profit from planting conventional corn. Natural variability in weather, pest infestations, and similar factors make profit uncertain, such that $F(\pi)$ and $f(\pi)$

characterize the cumulative distribution and probability density of random profit. $U(\pi)$ is the farmers utility of profit where $U'(\pi) > 0$ and $U''(\pi) \leq 0$—farmers are risk neutral or risk averse. The expected utility of profit is $EU = \int_{\underline{\pi}}^{\overline{\pi}} U(\pi)\, dF(\pi)$ where $\underline{\pi}$ and $\overline{\pi}$ represent the upper and lower bound of profit.

Switching from conventional to Bt corn changes expected utility by changing the distribution of profit. Lehman and Bradley have developed a convenient decomposition of the impact of this change in profit on expected utility:

$$(1) \qquad dEU = U'(\overline{\pi})\, d\mu_{\pi} + \int_{\underline{\pi}}^{\overline{\pi}} U''(\pi) \left\{ \int_{\underline{\pi}}^{\pi} dF(z)\, dz \right\} d\pi ,$$

where dEU is the change in expected utility, $d\mu_{\pi}$ is the change in expected net returns and $dF(\cdot)$ is the change in the cumulative distribution function. The first term on the right hand side of equation (1) is referred to as the mean effect and it represents the increase in expected utility due to an increase in average profit. The second term is referred to as the spread effect and represents the increase in expected utility due to reduced risk after accounting for the natural tendency of the variance of profit to increase with average profit. To understand the value of Bt corn, it is important to understand how Bt corn affects average profit and risk.

Let p be the price of corn and C be production costs exclusive of any technology fees paid for Bt corn. To reduce notational clutter and provide better focus, assume p and C are known and are the same for Bt and conventional corn. Abstract from the best management practices required by the Environmental Protection Agency for planting Bt corn, which currently require farmers to plant a minimum proportion of conventional corn. None of these simplifications detract from the implications of the analysis.

Let $y \geq 0$ be potential yield in the absence of European corn borer (ECB) and $1 \geq \lambda \geq 0$ be the proportion of potential yield lost to ECB. Potential yield is stochastic as a result of factors such as weather, random input availability, and damages from other pests and pathogens. The proportion of potential yield lost is also stochastic, not only due to random ECB populations, but also because of random environmental factors, the ability of crops to compensate, and variation in the timing of pest attacks.

ECB populations can be decimated during the brief adult mating period by dry weather (no rainfall, low relative humidity) and by wet weather at larval hatch (Mason et al.). Because cumulative weather over the season determines corn yield, these acute events during critical periods for ECB have little impact on yield and so no correlation exists between yield potential and the ECB population (Showers et al.). Therefore, we assume that potential yield and proportional yield loss are independent, an assumption consistent with the analysis of Hyde et al. The distribution and density functions of potential yield are $H(y)$ and $h(y)$ respectively, and μ_y and σ_y^2 denote the mean and variance of potential yield. The distribution and density functions of proportional yield loss are $G(\lambda)$ and $g(\lambda)$ respectively, and μ_λ and σ_λ^2 denote the mean and variance of proportional yield loss.

Profit from planting conventional corn is $\pi_0 = py(1 - \lambda) - C$. The mean and variance of conventional profit are $\mu_0 = p\mu_y(1 - \mu_\lambda) - C$ and $\sigma_0^2 = p^2(\sigma_y^2 + \sigma_L^2 - 2\sigma_{yL})$ where $L = y\lambda$ is total yield loss, σ_L^2 is the variance of this yield loss, and σ_{yL} is the covariance of yield and yield loss. Note the $\sigma_{yL} > 0$ because yield loss is an increasing function of yield, and yield and the proportion of yield loss are independent. Bt corn is virtually one-hundred percent effective, so profit from planting Bt corn is $\pi_1 = py - C - T$ where T is the additional technology fee paid to plant Bt. The mean and variance of Bt profit are denoted $\mu_1 = p\mu_y - C - T$ and $\sigma_0^2 = p^2\sigma_y^2$.

Comparing profit for Bt and conventional corn reveals that Bt corn will be more profitable on average if $p\mu_y\mu_\lambda > T$—if the expected yield loss is greater than the technology fee. However, the impact of Bt corn on profit variability may create an additional insurance benefit or cost, depending on the effect of Bt corn on the dispersion of profit after accounting for the change in average profit. Using the variance definitions just derived, Bt corn reduces the variability of profit if $\frac{\sigma_L}{\sigma_y} > 2\rho_{yL}$, where ρ_{yL} is correlation between potential yield and yield loss. If the ratio of the standard deviations is greater than twice the correlation coefficient between yield and losses, Bt corn reduces variability. Note that even though pest free yield y and proportional yield loss λ are independent, pest free yield and total yield loss $L = y\lambda$ are positively correlated, so that the right hand side of the condition is positive.

This condition implies that if the variance of yield loss is low relative to the variance of potential yield, then Bt corn is not likely to reduce risk if there is some degree of positive correlation in potential yields and yield loss. For Bt crops in areas where yield loss is quite variable and can approach 100%, it is likely that Bt crops will reduce the variance of yields unless the correlation between total pest losses and pest free yield is extraordinarily high. But in much of the Corn Belt, yield losses due to ECB are relatively small, on average less than 6% (Calvin), and a relatively minor component of total yield variability, so that Bt corn is could actually increase yield and profit variance.

Alternatively, the condition for Bt corn to reduce yield variance can be rewritten. Because total loss $L = y\lambda$ and y and λ are independent, $\rho_{yL} = \frac{\mu_\lambda \sigma_y}{\sigma_L}$ and

$\sigma_L = \mu_y \left(CV_y^2 \sigma_\lambda^2 + CV_y^2 \mu_\lambda^2 + \sigma_\lambda^2 \right)^{0.5}$, where $CV_y = \frac{\sigma_y}{\mu_y}$ is the coefficient of variation of pest free yield y. Given this, Bt corn reduces yield variance if

$$CV_y^2 < \frac{\sigma_\lambda}{\left(2\mu_\lambda - \sigma_\lambda^2 - \mu_\lambda^2\right)^{0.5}} . \tag{2}$$

This condition implies that given the mean and standard deviation of proportional yield loss for a location, which are independent of pest free yield, whether Bt corn increases or decreases yield (and profit) variability depends on yield variability.

While these results are suggestive, to better understand the impact of planting Bt corn on a farmer's risk, equation (1) indicates we need to evaluate $\int_{\underline{\pi}}^{\pi} dF(z)\,dz$. Let $F_0(\pi)$ and $f_0(\pi)$ be the cumulative distribution and density of profit with conventional corn. $F_1(\pi)$ and $f_1(\pi)$ is the cumulative distribution and density of profit with Bt corn. After transformation, $f_0(\pi) = \int_0^1 p^{-1}(1-\lambda)^{-1} h\left(\frac{\pi + C}{p(1-\lambda)}\right) g(\lambda)\, d\lambda$ and,

$f_1(\pi) = p^{-1} h\left(\frac{\pi + C + T}{p}\right)$. Integration yields $F_0(\pi) = \int_0^1 H\left(\frac{\pi + C}{p(1-\lambda)}\right) g(\lambda)\, d\lambda$ and,

$F_1(\pi) = H\left(\frac{\pi + C + T}{p}\right)$, such that

$$(3)\quad \int_{\underline{\pi}}^{\pi} dF(z)\,dz = \int_{\underline{\pi}}^{\pi}\left\{H\left(\frac{z+C+T}{p}\right)-\int_0^1 H\left(\frac{z+C}{p(1-\lambda)}\right)g(\lambda)\,d\lambda\right\}dz$$
$$= \int_{\underline{\pi}}^{\pi}\left\{\Pr\left(py-C-T\le z\right)-\int_0^1 \Pr\left(py-py\lambda-C\le z\right)g(\lambda)\,d\lambda\right\}dz \,.$$

Equation (3) offers some important insights into how planting Bt corn affects the distribution of profit. First, consider the case where farmers pay no technology fee. With no technology fee, $\pi_1 \geq \pi_0$ for all y and λ. Since $H(y)$ is non-decreasing, $\int_0^1 \Pr\left(py-py\lambda-C\le z\right)g(\lambda)\,d\lambda$ = (>) $\Pr\left(py-C\le z\right)$ when λ = (>) 0. Bt corn results in a second-order stochastic dominant shift in the distribution of profit while increasing average profit. Equation (1) then establishes that farmers are unequivocally better off planting Bt corn.

Once a technology fee is introduced, equation (3) unequivocally shows that Bt corn no longer results in a second order stochastic shift in the distribution of profit and whether average profit increases depends on the magnitude of the technology fee relative to the expected loss. Adding a technology fee eliminates the possibility of a second order stochastic dominance because it reduces the minimum possible profit. The minimum possible profit for conventional corn is the cost of production, – C. The minimum possible profit with Bt corn is the cost of production and technology fee, – C – T.

Therefore, $\Pr\left(py-C-T\le z\right) > \int_0^1 \Pr\left(py-py\lambda-C\le z\right)g(\lambda)\,d\lambda$ when $z < -C$. The maximum achievable profit for planting Bt corn is $p\bar{y}-C-T$, where $\bar{y}$ is the maximum potential yield. The maximum achievable profit for planting Bt corn is $p\bar{y}-C$.

Therefore, $\Pr\left(py - C - T \le z\right) > \int_0^1 \Pr\left(py - py\lambda - C \le z\right) g\left(\lambda\right) d\lambda$ when $z > p\bar{y} - C - T$.

Below $-C$ and above $p\bar{y} - C - T$ the distribution of profit for planting conventional corn dominates the distribution for planting Bt corn. Contrary to common perception, when a technology fee is charged, Bt corn increases the potential downside and decreases the potential upside.

The previous analysis dispels the myth that Bt corn necessarily provides insurance benefits to farmers by reducing yield risk. First, we showed how Bt corn could actually increase profit variability. Then we showed why Bt corn does not necessarily reduce downside or increase upside risk when a technology fee is charged. While the results are demonstrated for a proportional loss function, similar arguments suffice for other common loss functions. The first result depends on whether yield and yield loss are correlated. The second depends on the hypothesis that losses are sometimes negligible even without Bt corn. Yet, the practical significance of the results remains unclear.

If the results of Hyde et al. are representative of farmers throughout the Corn Belt, these results just developed here are merely academic and farmers and the EPA should include an insurance benefit when evaluating the value of Bt corn. However, if Bt corn significantly increases both yield variability and downside risk and decreases upside risk, then attributing an insurance benefit to Bt corn, as recommended in comments submitted to the EPA at a recent scientific advisory panel, creates an upward bias of the estimated value of Bt corn. Such a bias may mislead the development of regulatory policy and induce farmers to pay more for the technology than it is actually worth.

The insurance benefit offered by Bt corn is an empirical question. Existing evidence suggests there is a valuable insurance benefit, but this evidence is limited to one example from a region that does not experience substantial problems with ECB. The analysis also relies heavily on expert opinion, since at the time of the study there was little data available to obtain more concrete estimates of ECB losses on conventional and Bt corn. We now take advantage of recent field data from several states and several years to evaluate the proposition that Bt corn offers a substantial insurance benefit to farmers.

An Empirical Model

Because obtaining data on yield loss due to ECB is labor intensive and thus costly, particularly before the advent of Bt corn, most data are from short-term studies for only a few locations. Short-term data do not capture the full variability in ECB pressure and associated yield loss under the wide variety of yield conditions possible. Generalizing from short-term data collected at one location to other locations and to other years is also problematic—hence the reliance of some studies on expert opinion.

The method used in this study is to link long-term and geographically dispersed data with detailed yield data in a manner that allows greater generalization to other locations. We do not directly estimate the unconditional distribution of proportional yield loss $g(\lambda)$. Because yield loss depends on ECB and how much damage is caused to corn plants, we estimate conditional distributions that derive their underlying uncertainty from the unconditional distribution of the ECB pest population. By replacing the unconditional distribution of proportional yield loss with a conditional distribution depending on the ECB population, the model can be generalized to other locations. The final result is a stochastic model for the value of Bt corn parameterized by the distribution describing the local ECB population.

The unconditional distribution of pest damages is derived from conditional distributions in three steps. First, the unconditional distribution of the number of second generation ECB per plant is estimated.[1] Next the distribution of tunneling conditional on the number of second generation ECB is estimated. Finally, the distribution of proportional yield loss conditional on tunneling is estimated. Combining these distributions provides an estimate of the unconditional distribution proportional yield loss as function of ECB population parameters. Lastly, the unconditional distribution of potential yield is developed from USDA-NASS data.

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

Longitudinal data for state average second-generation ECB populations (4th or 5th instar ECB per plant) from Bullock and Nitsi were available for Illinois (1943-1984, 1987-1996), Minnesota (1963-1998), and Wisconsin (1963-1998). Examining histograms and time trends 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, a lognormal and gamma distribution with a time trend were fit to the data using maximum likelihood. Time trends were statistically insignificant at the 5% level and removed. We choose the lognormal distribution since it produced a higher maximized value for the log-likelihood function than the gamma distribution with the same number of parameters (Pollack and Wales). The Durbin-Watson test using a 5% level of significance indicated no significant autocorrelation in the prediction errors for the lognormal distribution.

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[1] Most regions of the Corn Belt experience two generations of ECB per year. However, most field collection efforts focus only on obtaining estimates of second-generation populations.

These results agree with the literature. Chiang and Hodson do not find significant correlation in ECB populations from one year to the next over a ten-year period at a location in Minnesota. Similarly, in a five-year study, Chiang et al. found that first generation ECB densities were not correlated with the second-generation density of the previous fall and the over-wintering density from the same spring. Showers et al. found the surviving ECB population is independent of egg laying by the previous generation and that short term climatic conditions explained 83-91% of the variation in populations.

Based on our analysis and these findings, we assume an unconditional distribution for the annual population of second-generation 4^{th} and 5^{th} instar ECB larvae per plant. Table 1 reports estimates of the median *m* and shape parameter *s* of the lognormal density for each state, as well as the implied mean and coefficient of variation of the ECB population. Calvin reports county level data for 1960-1969 for Boone County, IA, and Hall and Cuming Counties, NE. Following the previous analysis, Table 1 reports estimates for the same parameters for each county.

ECB Tunneling: $t \sim w(t \mid n)$

ECB cause yield loss by tunneling, which reduces nutrient and water flow to developing ears, accelerates senescence, exposes plants to pathogens, and causes stalk lodging and ears to drop (Mason et al.). Because many factors influence the amount of tunneling per individual ECB (e.g. hybrid planted, corn phenology during stalk boring, age and health of the ECB, temperature during boring), total tunneling depends stochastically on the ECB population. Field-level data collected in 1997 from Bt field trials conducted by collaborators in 9 states (IA, IL, MD, MN, MO, NE, OH, SD, and

WI) were obtained from Monsanto. The average number of second-generation larvae per plant and average tunneling (cm) were reported for 292 Bt fields and 211 non-Bt fields. Most of the fields (76.7%) were from sites in IA, IL, and NE. Because Bt corn provided effective control of ECB—the average number of larvae per plant was 0.006 and average tunneling was 0.050 cm—only data from non-Bt fields are used for estimation. Figure 1 plots observed field average tunneling against observed field average ECB larvae for the non-Bt fields.

Field average tunneling must be strictly non-negative. Furthermore, conditional histograms of tunneling indicated that as the larval population increased, histograms changed from L-shaped to unimodal curves with rightward skewing. As such, a gamma or lognormal density seemed appropriate. The data also indicated that the standard deviation of tunneling increased approximately linearly with the ECB population. Figure 1 indicates that as the ECB population increases, average tunneling increases less than proportionally. Various maximum likelihood models were evaluated for the distribution of tunneling conditional on the ECB population, assuming a gamma or lognormal distribution. Several non-linear models were evaluated for mean tunneling, including combinations of linear, quadratic, negative exponential, square root and hyperbolic terms. In all cases a zero intercept was imposed.

The model that included both a linear term and a square root term for the mean as a function of the ECB population performed best ($R^2 = 0.822$). The lognormal distribution is used since it yielded a higher maximized value of the log-likelihood function than the gamma distribution with the same number of parameters (Pollack and Wales). As a result, $w(t \mid n) = \frac{1}{ts\sqrt{2\pi}} \exp\left(-\frac{\ln(t/m)^2}{2s^2} \right)$, where $s =$

$\left[\ln\left(\left(a_1 n + a_2\sqrt{n}\right)^2 + \left(b_0 + b_1 n\right)^2\right) - \ln\left(\left(a_1 n + a_2\sqrt{n}\right)^2\right)\right]^{0.5}$ and $m = \left(a_1 n + a_2\sqrt{n}\right)^2 /$ $\sqrt{\left(a_1 n + a_2\sqrt{n}\right)^2 + \left(b_0 + b_1 n\right)^2}$ are the shape parameter and median of the lognormal distribution, and a_1, a_2, b_0, and b_1 are parameters to estimate. Since the mean of the lognormal density is $m\exp(0.5s^2)$ and the standard deviation is $m\exp(s^2)\sqrt{\exp(s^2)+1}$, mean tunneling is $a_1 n + a_2\sqrt{n}$ and the standard deviation is $b_0 + b_1 n$. Figure 1 also plots the estimated mean with the observed data and Table 2 reports parameter estimates.

Though data were from several locations in the Corn Belt, all observations were from one year. Because environmental conditions that vary from year to year may influence the relationship between ECB larvae and tunneling and more data are not currently available to address this variation, sensitivity analysis determines how robust conclusions are to parameter estimates.

Proportion of Yield Lost: $\lambda \sim q(\lambda \mid t)$

Data from on-farm field trials conducted by several cooperating farmers in 22 counties in Iowa from 1997-1999 are used to estimate the distribution of proportional yield loss conditional on ECB tunneling. A Bt hybrid and a non-Bt isoline hybrid were planted side by side and yield for each strip determined by machine harvest. Data were available for three different Bt events (MON810, Bt11, DBT418) in a variety of hybrids. A total of 138 observations were available that included Bt yield, non-Bt yield, and measured stalk tunneling due to ECB. The yield loss due to ECB was converted to a proportion of the Bt yield since average yields differed across locations and years. Figure 2 plots the observed proportion of yield lost versus observed ECB tunneling.

Conditional histograms indicated a symmetric distribution, so a normal distribution was assumed. The mean loss increased with the ECB population at a decreasing rate. Also, the mean loss logically should approach some maximum. As such, a negative exponential model seemed appropriate so that the proportional yield loss asymptotically approaches the maximum. Figure 2 indicates that the variability of loss decreases as the ECB population increases. To capture this trend, a linear model is used for the standard deviation as a function of the ECB population. Given these assumptions, the conditional distribution of proportional yield loss is normal with mean $\bar{\lambda}(1-\exp(-\kappa t))$ and standard deviation $d_0 + d_1 t$, where $\bar{\lambda}$ is the maximum expected proportional yield loss, κ determines the rate of increase toward the maximum, and d_0 and d_1 are respectively the estimated intercept and slope of the standard deviation as a function of ECB tunneling t. Table 3 reports maximum likelihood estimates of the parameters. Figure 2 illustrates the model fit by plotting the estimated conditional mean.

Treating the predicted mean as a regression prediction, $R^2 = 0.366$. The low R^2 results because the data exhibit substantial variation for any given level of tunneling. This result is consistent with published research concerning ECB damage that finds other factors such as corn phenology and weather also contribute to deviations from pest free yields (Bode and Calvin; Calvin et al.; Jarvis et al.). Other researchers report similar low correlation between ECB tunneling and yield loss (Berry and Campbell; Lynch, Robinson, and Berry). Again, sensitivity analysis indicates the robustness of results to damage model assumptions.

Note that the proportion lost is negative for 38 observations (27.5%) because the non-Bt hybrid yielded more than the Bt hybrid. As yield monitor data show, yields from contiguous strips do differ, even when under the same treatment, as a result of site-specific differences that vary from year to year (Bakhsh et al.). The observed negative losses occurred at low observed tunneling and are due to these random site-specific differences. These random site-specific errors are not pertinent to the analysis here and so the additive normal error is dropped. However, to preserve the inherent randomness in proportional yield loss conditional on tunneling, the parameters κ and $\bar{\lambda}$ are treated as random—following the normal distribution with the estimated mean and a standard deviation equal to the estimated standard error.

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

The beta distribution is a commonly assumed density for crop yields (Nelson and Preckel, Hennessy and Babcock). As such, we assume pest free yield follows a beta distribution with four parameters—the minimum and maximum potential yield, plus two shape parameters α and ω. The four-year average (1997-2000) of the state average corn yield reported in USDA-NASS data available on-line are used for Illinois, Minnesota and Wisconsin. The four-year average (1997-2000) of the county average corn yield are used for Boone county, IA (dryland) and Cuming and Hall counties, NE (irrigated). These averages are reported in Table 6.

Field-level variability of corn yields is much higher than for county level or state level yields because the area averaged across is much smaller. As a reasonable assumption, the coefficient of variation for corn yield is set at 30%. For comparison, Hennessey, Babcock and Hayes report a coefficient of variation of 29.4% as the average for 10 corn farms in Sioux County, IA.

Minimum yield was assumed to be zero for total crop loss. Maximum yield was set at the mean yield plus two standard deviations. However, because the standard deviation is determined by the mean, maximum yield is simply 1.6 larger than the mean yield. Given the mean, standard deviation, minimum, and maximum, the shape parameters α and ω are determined by first rescaling the beta density to the standard minimum of zero and maximum of one. The rescaled mean is 1/1.6 = 0.625 and, because the standard deviation is assumed to be 30% of the mean, the rescaled standard deviation is 0.3/1.6 = 0.1875. Given these, the standard formulas for the mean and standard deviation as functions of the parameters α and ω are inverted to obtain the implied α and ω for this mean and standard deviation, namely $\alpha = 3.542$ and $\omega = 2.125$.

This analysis assumes pest free yield is uncorrelated with the ECB population and thus uncorrelated with observed ECB damage. As previously argued, empirical evidence supports this independence assumption, since yields depend on cumulative weather events throughout a season, while weather events during critical life stages greatly influence ECB populations (Showers et al.).

The Value of Bt Corn

Given the series of conditional distributions and the assumed density functions, Monte Carlo integration (Greene) is used to solve the needed integrals to determine the effect of switching from conventional to Bt corn on the mean and variance of profit. A C++ program using algorithms reported Press et al. was developed to draw random variables and conduct the analysis. Experimentation indicated that 50,000 random variates for each probability density were sufficient for estimates to stabilize.

Table 4 reports the mean proportional yield loss as a percentage over a wide range of ECB population means and coefficients of variation. As expected, as the mean ECB population increases, the expected proportional yield loss increases. The ECB population's coefficient of variation has some effect. Because the proportional yield loss is concave in the realized ECB population, as the coefficient of variation increases, the expected proportional yield loss decreases. Table 4 can be used to determine the expected profit change from planting Bt corn. Because the ECB coefficient of variation has a minor impact, a reasonable estimate of proportional yield loss can be determined from just the ECB mean. The product of this expected loss, the expected yield and expected price can then be compared directly to the technology fee.

Table 6 reports the results of such an analysis for the six locations with ECB population data, assuming a corn price of $2.00 and the reported mean yields in the table. The results indicate an expected profit increase ranging from a high of $22.68 in Hall county, NE to a low of $12.26 in Wisconsin. For these price and mean yield assumptions, these results indicate sufficient value to planting Bt corn to cover the typical technology fee of $10.00 in all these locations. However, this analysis does not take variance changes into account.

For the same wide range of ECB population means and coefficients of variation, Table 5 reports the critical coefficient of variation for pest free yield calculated using equation (2). A coefficient of variation for pest free yield that exceed this critical value means that Bt corn increases yield variance, while a coefficient of variation below this critical value decreases yield variance. Over this wide range of ECB population assumptions, Table 5 indicates that the pest free yield coefficient of variation must remain fairly low (generally < 10%) for Bt corn to decrease the variance of profit. Indeed, given the results in Table 5, it seems likely that Bt corn will increase the variance of profit for almost all growers, since this range of ECB population parameters should cover most areas that have economically important ECB populations.

Again assuming corn price of $2.00 and using the reported mean yields, Table 6 reports the increase in the standard deviation of profit due to switching to Bt corn for the six locations with ECB population data. The increase ranges from $3.23 per acre in Wisconsin to $6.42 per acre in Hall county, NE, or about a 4-7.5% increase. However, quantifying the impact of these variance increases on Bt corn adoption incentives requires specify a utility function in order to estimate expected utility. Changes in adoption incentives are monetarized by inverting the utility function to convert expected utility to certainty equivalents, then using the difference in certainty equivalents to estimate farmer willingness to pay for Bt corn.

A negative exponential utility function is assumed since it exhibits constant absolute risk aversion, which eliminates wealth effects, and serves as a reasonable approximation of preferences. Following Babcock, Choi, and Feinerman, the constant of absolute risk aversion (R_a) is chosen so that the implied risk premium is a reasonable percentage of the standard deviation of profit. For results reported in Table 6, the price of corn is $2.00 per bushel and mean yield is as reported in Table 6. The average of the standard deviation of profit with conventional and Bt corn is used. For moderate risk aversion, the risk premium is 20% of the average standard deviation of profit, while for extreme risk aversion it is 40%. Table 6 reports the associated constants of absolute risk aversion for each location.

Using these values of R_a for each location, Monte Carlo integration is used to estimate expected utility for conventional and Bt corn, then certainty equivalents are calculated as $-\ln(1-EU)/R_a$, where EU is expected utility. Table 6 then reports the estimated willingness to pay (WTP) for Bt corn, calculated as the difference in certainty equivalents, for assuming R_a for both the 20% and 40% risk premiums. These estimates of WTP indicate that relative to the risk neutral farmer, the variance increase associated with planting Bt corn reduces the value of Bt corn by about 12% for moderately risk averse farmers and by about 27% for extremely risk averse producers. The magnitude of these adjustments for risk aversion imply that ignoring the variance increasing impact of Bt corn leads to a significant bias in estimating the value of Bt corn.

Table 6 also reports Monte Carlo estimates of the mean and standard deviation of proportional yield loss and total yield loss, the correlation between pest free yield and total yield loss, and the critical value of the pest free yield coefficient of variation, above which Bt corn increase the variance of yield and profit. These results are as expected given the results reported in Tables 4 and 5.

To graphically evaluate equation (3), Figure 3 plots the empirical cumulative probability distributions of profit for Minnesota for conventional and Bt corn. The assumed corn price is $2.00, yield mean as reported in Table 6 (145), and the cost of production C = $180.00, a reasonable estimate obtained from University if Minnesota Extension budgets. The top plot assumes a technology fee T = $0, while the bottom plot assumes the more typical technology fee of T = $10.00. The top plot shows that when no technology fee is charged, Bt corn first-order stochastically dominants conventional corn—Bt corn has the same maximum and minimum profit outcomes, but a higher mean.

The bottom plot shows that with a technology fee, stochastic dominance of conventional corn by Bt corn is no longer possible, since Bt corn has more probability mass at low profit realizations—the technology fee changes the distribution of profit so that the minimum profit with Bt corn is now less than that for conventional corn.

Results reported here are contrary to those reported by Hyde et al. ECB population data for Indiana were not available to estimate population parameters and thus conduct simulations to generate results for Indiana comparable to those reported for other locations. However, equation (2), which indicates whether Bt corn increases or decreases yield variability, demonstrates that the source of the difference stems from differences in the estimated variability of pest free yield and the correlation between pest free yield and yield losses. Using probabilities and yields reported by Hyde et al. for the various branches of their probability tree, their estimated model implies a mean yield of 131.7 bushels, with a coefficient of variation of 14.56%, and a mean proportional yield loss of 1.42%, with a standard deviation of 2.75%. Using equation (2), these statistics for proportional yield loss imply a critical coefficient of variation for pest free yield of 16.6%, which is greater than the estimated yield coefficient of variation. As such, their estimated model implies that Bt corn decreases yield variance, as they correctly conclude.

Conclusion

Bt corn offers farmers a powerful new tool for controlling European corn borer (ECB), but it is not always clear when the value of Bt corn is worth the added technology fee. The common perception is that the value of Bt corn has two important components. First, Bt corn increases profits by reducing yield losses from ECB. Second, Bt corn reduces profit variability by reducing the variability of yield losses from ECB. This perception has framed the decision to buy Bt corn in the context of the decision to buy insurance, which encourages farmers and the Environmental Protection Agency to add a risk benefit to their calculations of the value of Bt corn. But previous work concerning pesticides shows that pest control, even complete pest control such as Bt corn offers, does not necessarily reduce risk and hence provide insurance benefits.

Analytically, we derive the conditions under which Bt corn will increase the variability of profits. We find that when the variation of yield losses attributable to ECB is low relative to other natural sources of variation in the potential yield and there is positive correlation between yields and yield losses, Bt corn tends to increase profit variance. We also show that when a technology fee is charged planting Bt corn tends to increase downside risk, while also decreasing upside risk. Together, these results dispel the conventional wisdom that Bt corn necessarily provides an insurance benefit.

An empirical application based on the analytic framework shows that the potential for Bt corn to increase risk is more than a theoretical possibility. Not surprisingly, the analysis finds that Bt corn is valuable to many growers and that the primary source of this value is reduced yield losses. However, the analysis also indicates that Bt corn increases profit variability and so increases, not decreases, risk. As a result, risk averse farmers should not pay more for Bt corn than the expected value of increased yields and the EPA should not increase estimates of the value of Bt corn to farmers above the estimated expected value of increased yield to account for the insurance benefit. Indeed, our analysis indicates that the increased risk can decrease the value of Bt corn as much as 10-25% depending on risk preferences.

Table 1. Maximum likelihood estimates of median *m* and shape parameter *s* (standard errors in parentheses) for the lognormal density of ECB per plant, plus calculated mean and coefficient of variation.

Location	*m*	p value	*s*	p value	Mean	Coefficient of Variation
Illinois[a]	0.976	<0.001	0.641	<0.001	1.199	0.713
	(0.087)		(0.063)			
Minnesota[a]	0.588	<0.001	0.796	<0.001	0.807	0.940
	(0.078)		(0.094)			
Wisconsin[a]	0.379	<0.001	0.867	<0.001	0.551	1.058
	(0.055)		(0.102)			
Boone County, IA[b]	0.621	<0.001	0.784	<0.001	0.845	0.922
	(0.154)		(0.175)			
Cumming County, NE[b]	1.429	<0.001	0.711	<0.001	1.840	0.811
	(0.321)		(0.159)			
Hall County, NE[b]	1.591	<0.001	0.498	<0.001	1.801	0.531
	(0.251)		(0.111)			

[a] Using state average data from Nitsi and Bullock.

[b] Using county data from Calvin.

Table 2. Maximum likelihood estimates of parameters for $w(t \mid n)$, the distribution of tunneling (cm) conditional on the second-generation ECB larvae population.

Parameter	Estimate	Standard Error	p value
a_1	2.555	0.8393	0.002
a_2	5.654	1.0221	<0.001
b_0	3.397	0.7563	<0.001
b_1	1.730	0.5534	0.002

Table 3. Parameter estimates and associated statistics for $q(\lambda \mid t)$, the distribution of the proportion of yield lost λ conditional on tunneling *t*.

Parameter	Estimate	Standard Error	p value
$\bar{\lambda}$	0.1014	0.0170	<0.001
κ	0.1618	0.0613	0.008
d_0	0.06587	0.00526	<0.001
d_1	-0.002302	0.000794	0.004

Table 4. Average proportion of yield lost over a range of assumptions for the ECB population mean and coefficient of variation.

	ECB Coefficient of Variation							
ECB Mean	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2
0.5	4.7%	4.7%	4.6%	4.5%	4.4%	4.4%	4.3%	4.2%
0.6	5.1%	5.0%	5.0%	4.9%	4.8%	4.7%	4.6%	4.6%
0.7	5.4%	5.4%	5.3%	5.2%	5.1%	5.0%	4.9%	4.9%
0.8	5.7%	5.6%	5.6%	5.5%	5.4%	5.3%	5.2%	5.1%
0.9	6.0%	5.9%	5.8%	5.7%	5.6%	5.5%	5.4%	5.3%
1.0	6.2%	6.1%	6.0%	5.9%	5.8%	5.7%	5.6%	5.5%
1.1	6.4%	6.3%	6.2%	6.1%	6.0%	5.9%	5.8%	5.7%
1.2	6.6%	6.5%	6.4%	6.3%	6.2%	6.1%	6.0%	5.9%
1.3	6.8%	6.7%	6.6%	6.5%	6.4%	6.3%	6.2%	6.1%
1.4	6.9%	6.8%	6.7%	6.6%	6.5%	6.4%	6.3%	6.2%
1.5	7.1%	7.0%	6.9%	6.8%	6.6%	6.5%	6.4%	6.3%
1.6	7.2%	7.1%	7.0%	6.9%	6.8%	6.7%	6.6%	6.5%
1.7	7.3%	7.2%	7.1%	7.0%	6.9%	6.8%	6.7%	6.6%
1.8	7.5%	7.3%	7.2%	7.1%	7.0%	6.9%	6.8%	6.7%
1.9	7.6%	7.5%	7.3%	7.2%	7.1%	7.0%	6.9%	6.8%
2.0	7.7%	7.6%	7.4%	7.3%	7.2%	7.1%	7.0%	6.9%

Table 5. Critical coefficient of variation for pest free yield, above which Bt corn increases the yield variance and below which Bt corn decreases yield variance, over a range of ECB population means and coefficients of variation.

	ECB Coefficient of Variation							
ECB Mean	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2
0.5	9.0%	9.2%	9.4%	9.6%	9.8%	10.0%	10.2%	10.4%
0.6	8.7%	8.9%	9.1%	9.4%	9.6%	9.8%	10.0%	10.2%
0.7	8.5%	8.7%	8.9%	9.1%	9.4%	9.6%	9.8%	10.0%
0.8	8.2%	8.5%	8.7%	8.9%	9.2%	9.4%	9.6%	9.8%
0.9	8.0%	8.3%	8.5%	8.7%	9.0%	9.2%	9.4%	9.6%
1.0	7.9%	8.1%	8.3%	8.6%	8.8%	9.0%	9.3%	9.5%
1.1	7.7%	7.9%	8.2%	8.4%	8.7%	8.9%	9.1%	9.3%
1.2	7.6%	7.8%	8.1%	8.3%	8.5%	8.8%	9.0%	9.2%
1.3	7.4%	7.7%	7.9%	8.1%	8.4%	8.6%	8.8%	9.0%
1.4	7.3%	7.5%	7.8%	8.0%	8.3%	8.5%	8.7%	8.9%
1.5	7.2%	7.4%	7.7%	7.9%	8.1%	8.4%	8.6%	8.8%
1.6	7.1%	7.3%	7.6%	7.8%	8.0%	8.2%	8.5%	8.7%
1.7	7.0%	7.2%	7.4%	7.7%	7.9%	8.1%	8.4%	8.6%
1.8	6.9%	7.1%	7.4%	7.6%	7.8%	8.1%	8.3%	8.5%
1.9	6.8%	7.0%	7.3%	7.5%	7.7%	7.9%	8.2%	8.4%
2.0	6.7%	6.9%	7.2%	7.4%	7.6%	7.9%	8.1%	8.3%

Table 6. Summary of results for each location.

Variable	Illinois	Minnesota	Wisconsin	Boone County, IA	Cuming County, NE	Hall County, NE
Mean Yield μ_y	140.25	145.00	136.00	151.83	151.50	153.00
St. Dev. Yield σ_y	42.08	43.50	40.80	45.55	45.45	45.90
Mean π_0	82.46	94.40	80.25	107.02	101.33	103.13
Mean π_1	100.36	109.87	92.51	123.58	122.97	125.81
Expected Profit Change $d\mu_\pi$	17.89	15.46	12.26	16.56	21.64	22.68
St. Dev. π_0	78.85	82.81	78.03	86.97	84.48	85.38
St. Dev. π_1	83.69	86.92	81.26	91.47	90.48	91.80
St. Dev. Profit Change $d\sigma_\pi$	4.85	4.11	3.23	4.50	6.00	6.42
R_a, 20% Risk Premium	0.00506	0.00484	0.00516	0.00461	0.00470	0.00464
R_a, 40% Risk Premium	0.01108	0.01061	0.01131	0.01009	0.01029	0.01016
WTP 20% Risk Premium	15.74	13.67	10.82	14.61	19.00	19.90
WTP 40% Risk Premium	13.03	11.35	8.99	12.15	15.72	16.46
Mean Loss μ_λ	0.064	0.053	0.045	0.055	0.071	0.074
St. Dev. Loss μ_λ	0.028	0.030	0.030	0.030	0.028	0.026
Critical Yield CV	8.1%	9.2%	10.0%	9.1%	7.6%	6.9%
Mean Total Loss μ_L	8.96	7.74	6.11	8.28	10.82	11.34
St. Dev. Total Loss σ_L	4.92	5.04	4.58	5.33	5.49	5.39
Correlation Coefficient ρ_{yL}	0.537	0.457	0.402	0.470	0.589	0.634

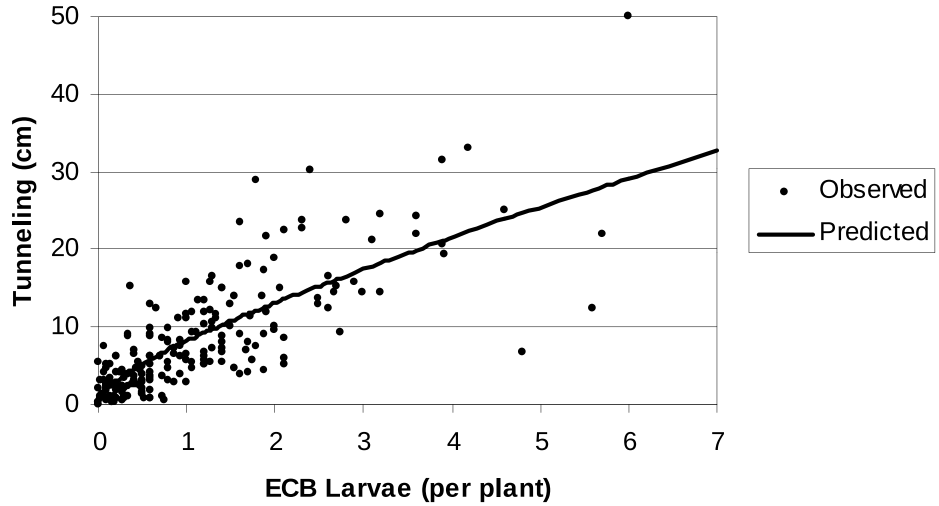

Figure 1. Observed and predicted field average tunneling (cm) versus field average second generation 4th and 5th instar ECB population per plant.

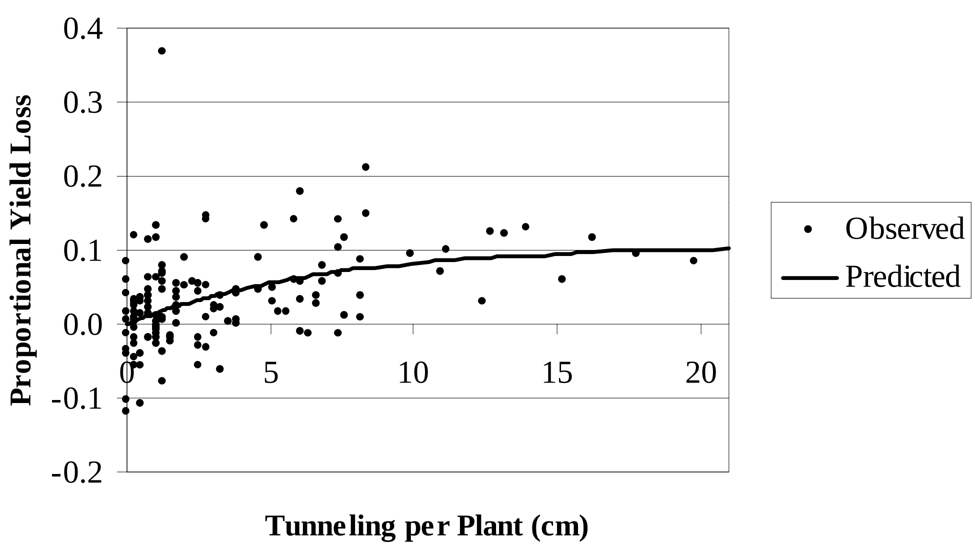

Figure 2. Observed and predicted proportional yields loss versus field average tunneling.

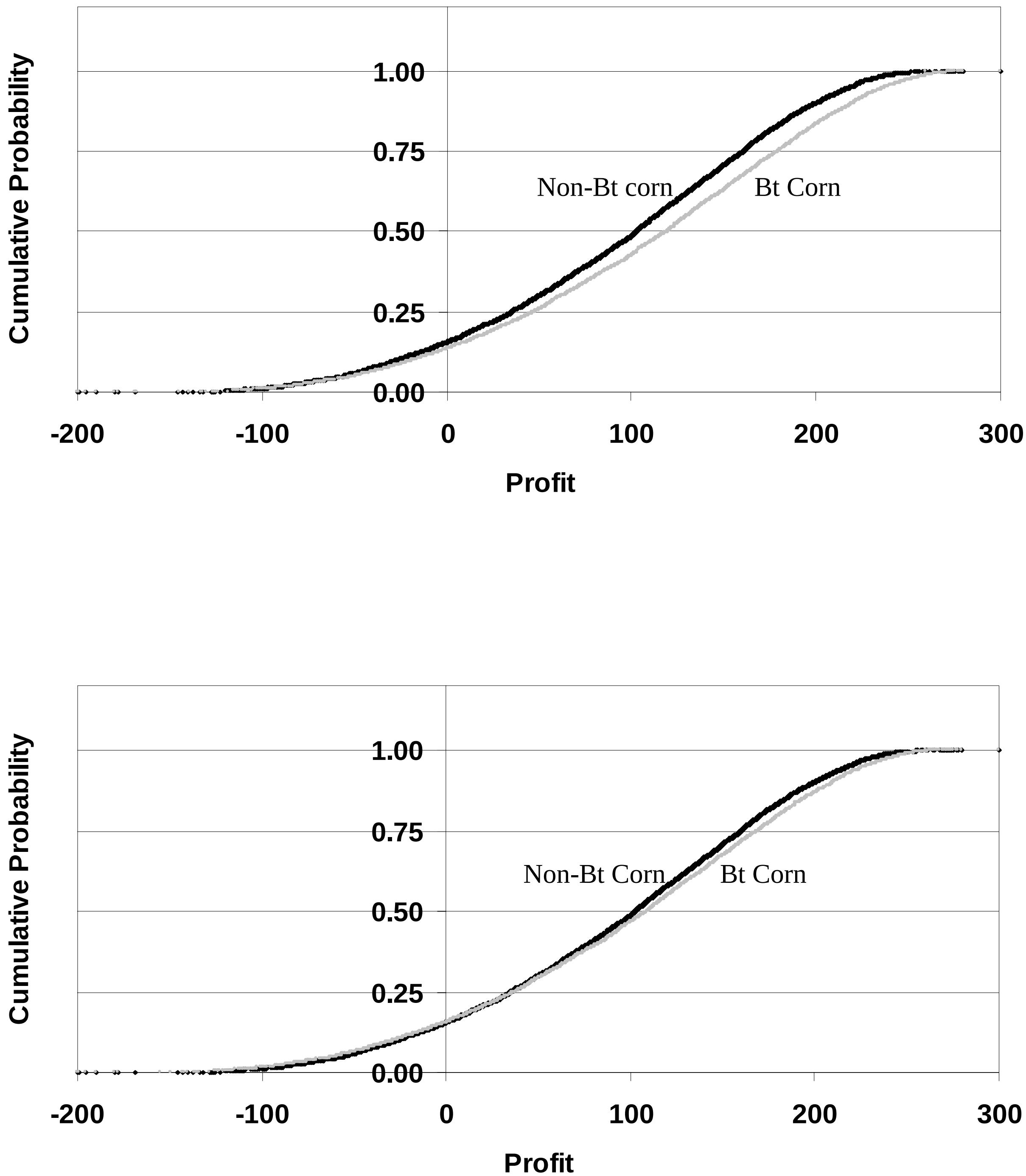

Figure 3. Plots of the empirical cumulative distributions of profit for non-Bt corn and Bt corn with no technology fee (top) and with a $10 technology fee (bottom).

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