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Is Bt Corn Really a Drag? Bt Corn Yield Drag and Yield Variance

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Abstract

The effect of Bt corn on the mean and variance of yield is decomposed into separate effects from second-generation European corn borer control and from factors such as yield drag, secondary pest suppression, and genetic linkages. For the systems investigated, Bt corn increases mean yield 2.8-6.6% and increases yield variance as much as 7.9% by eliminating ECB damage. No evidence for a yield drag is found, but rather support for a Bt corn yield boost that increases mean yield an additional 1.65% and yield variance an additional 3.5-3.7%. This yield boost constitutes 20-40% of the farmer willingness to pay for Bt corn.

Introduction

Bt corn is a popular term used to describe corn engineered to contain genetic material from the soil bacterium *Bacillus thuringiensis* (Bt). This genetic material allows Bt corn to produce proteins that are toxic to insects such as the European corn borer (*Ostrinia nubilalis* Hübner: ECB)—a pest estimated to cost farmers over $1 billion annually in yield loss and control costs (Mason et al.). Bt corn offers complete control of the targeted pest, which has resulted in its rapid adoption in the U.S. since commercial introduction in 1996. Over 25% of all corn acreage in the U.S. was planted to Bt corn in 2003, with higher adoption rates in areas with larger yield losses from ECB damage (USDA-NASS 2003).

Bt corn increases harvested yield by controlling ECB and so eliminating crop damage from the pest. However, the effect of Bt corn on the yield may reach beyond its control of ECB. Bt corn plants must devote nutrients and energy to producing proteins that are toxic to ECB, but do not directly contribute to a higher yield. As a result, some speculation exists that Bt corn may suffer from yield drag—a decrease in yield potential due to the introduction of the Bt gene (Coaldrake).[1] Yield drag has been demonstrated for other genetically engineered crops such as herbicide tolerant soybeans (Elmore et al.; Benbrook 1999).

The evidence for Bt corn generally does not support the yield drag hypothesis (Graeber, Nafziger and Mies; Minor et al.; Nielsen; Willson). However, the only peer-reviewed study among these (Graeber, Nafziger and Mies) evaluates an unnamed experimental Bt hybrid that may never have been commercialized. Furthermore, none of these studies explicitly controls for ECB damage when testing for a yield drag, and so do not determine whether the observed yield differences are due to ECB control or yield drag. Bt proteins are toxic to insect pests other than ECB, so that the yield protection provided by Bt corn extends beyond the target pest, which may have an additional effect on yield (Mason et al.). The potential also exists for genetic linkages between the Bt gene and other genes that can increase or decrease yield. Linkage with deleterious genes would have a negative effect on yield potential, while linkage with favorable genes would have a positive effect on yield potential.[2]

This paper explores how Bt corn changes the distribution of harvested yield as a result of improved ECB control and factors such as yield drag, secondary pest control, and genetic linkages. First, data from Bt field trials are analyzed to separately identify the effects of ECB control and these other factors on the distribution of harvested yield. Next, to determine the economic significance of these effects, an empirical model is developed to weigh the economic benefits and costs of these separate effects against the benefits from better ECB control. Lastly, results and potential policy implications are discussed.

Statistical Analysis of the Effect of Bt Corn on Yield

Data from on-farm field trials conducted from 1997-1999 by cooperating farmers in 22 Iowa counties are used to estimate the effect of Bt corn on the distribution of yield loss.[3] Collected data included machine harvested yields for Bt and non-Bt isoline hybrids planted side-by-side and stalk tunneling by second-generation ECB larvae in the non-Bt strip. Let y_0 and y_1 denote harvested yield (bu/ac) for conventional (non-Bt) corn and Bt corn respectively and let t denote stalk tunneling (cm/plant) by ECB larvae. Three Bt events (Monsanto's MON810, Dekalb's DBT418, Novartis's Bt11) were evaluated in a variety of hybrids. Table 1 reports the number of observations for each event-year combination for which data were collected.

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[1] Many examples can also be found in the popular farm press and similar media discussing transgenic crops.
[2] Yield drag is different from yield lag. Yield drag is a lower yield potential in genetically equivalent hybrids (isolines). Yield lag exists when new traits are not yet available in elite hybrids. Initial hybrids with the new trait have lower yield potentials because they are genetically inferior to the elite hybrids. However, once the new trait is available in elite hybrids, the yield lag disappears, though a yield drag may still exist.
[3] The data for 1997 and 1998 are summarized by Rice and by Farnum and Pilcher respectively.

Since genetic engineering does not affect conventional corn, the conventional yield is potential yield adjusted only for pest damage. Let y be potential yield and l be the proportion of this potential yield lost due to ECB damage, so that conventional yield is $y_0 = y(1 - l)$. Since the evaluated Bt corn events eliminate all ECB, harvested yield with Bt corn is only affected by factors not depending on ECB, such as yield drag and suppression of other insect pests. Let d be the proportional change in potential yield that results from these effects, whatever their source, so that yield with Bt corn is $y_1 = y(1 - d)$. Let z be the observed proportional difference between Bt and non-Bt yields: $z = (y_1 - y_0)/y_1$. Substituting the definitions of y_0 and y_1 into this expression gives $z = (l - d)/(1 - d)$.

Yield loss l depends on ECB damage as measured by tunneling t, but yield drag d should by definition be independent of ECB tunneling. In addition, other uncontrolled factors (e.g., soil heterogeneity, input application errors, measurements errors) contribute to variability in the observed proportional difference between the Bt and non-Bt yields (z). These random factors may or may not depend on tunneling t. As a result, the experimental data were used to estimate models of the following general form via maximum likelihood:

(1) $$z = \frac{l(t) - d}{1 - d} + t(t)e,$$

where $e \sim N(0,1)$ and d and the parameters of $l(t)$ and $t(t)$ must be estimated. All models assumed zero loss due to ECB when no tunneling occurs ($l(0) = 0$).

A linear and several nonlinear models for $l(t)$ were estimated for each event-year assuming a constant variance ($t(t) = t$). Nonlinear models included quadratic, negative-exponential, Cobb-Douglas, and hyperbolic models. Results are not reported, but nonlinear models performed poorly relative to the linear model $l = at$. Most nonlinear parameters were insignificant for all event-years and the R-squared increased little relative to the linear model. Therefore, the linear model for l was used for all subsequent estimations. Next, to account for possible heteroscedasticity, linear models for t of the form $t = t_0 + t_1 t$ were estimated for each event-year. Results are not reported, but estimation failed to converge for most event-years, and for those that did, estimates of t_1 were insignificant. Given these results, table 1 reports estimation results for each event-year using the linear model for l and a constant variance t:

(2) $$z = \frac{at - d}{1 - d} + te \ .$$

Equation (2) implies that ECB tunneling does not affect the proportional difference between Bt and non-Bt yields (z), except through the proportional yield loss l, and that the effects of Bt corn separate from any effects due to ECB control occur only through d.

In table 1, the estimated slope parameter a is significant for MON810 in 1997 and 1999 and DBT418 in 1997, supporting the conclusion that ECB tunneling reduces yield. The estimated d for each event-year is negative and significant only at the 10% level for MON810 in 1997 and 1998, the event-years with the most observations. Since d is defined as the proportional decrease in potential yield, a negative d implies that the mean yield for Bt corn is greater than for the paired non-Bt corn and this difference is separate from any effects Bt corn has on mean yield due to ECB control.

Likelihood ratio tests were used to determine whether common parameters were equal across event-years, assuming event-year specific estimates for a, d, and t for the unrestricted model. Results are not reported, but the tests strongly supported a model with a common a and d across all events and years, with a different t for each event-year:[4]

(3) $$z = \frac{at - d}{1 - d} + \sum_{i=1}^{5} D_i t_i e \; .$$

D_i is an indicator variable for the five event-year combinations (D_i = 1 for event-year i and 0 otherwise) and t_i is the event-year specific estimate of t.

Equation (3) implies that both the proportional loss in potential yield for one centimeter of stalk tunneling by ECB larvae (a) and the proportional reduction of mean yield for Bt corn relative to equivalent non-Bt corn (d) are the same for all event-years. However, the variance of z due to statistical noise from experimental errors and similar factors (t) are specific to each event-year. These results seem reasonable, since weather and related growing conditions vary each year and hybrids perform differently under similar growing conditions. However, the effect of ECB stalk tunneling should on average be similar across years and events, as should d if it captures effects such as yield drag.

Bt Corn Yield Boost

Table 2 reports parameter estimates for the equation (3) model. The estimated a of 0.0052 implies that on average potential yield is decreased over 0.5% for each centimeter of stalk tunneling by ECB (over 1.3% per inch). The estimated d is negative, implying that the yield potential for Bt corn is on average 1.65% greater than for the conventional hybrid, regardless of the ECB damage. These results imply that Bt corn does not have a yield drag, but rather a yield boost averaging 1.65% that occurs in addition to any increase in mean yield due to ECB control.

[4] Likelihood ratio tests failed to reject the equation (3) model versus a model with separate event-year equations as reported in table 1 (p = 0.428) and rejected models with a common t and heteroscedasticity versus the equation (3) model (all with $p < 0.001$).

We hypothesize three sources for this yield boost: (1) elimination of yield loss due to first-generation ECB larvae, (2) a suppression benefit from controlling other corn insect pests, and (3) an increased yield potential due to continued breeding of the Bt hybrid relative to the conventional hybrid or genetic linkages.

In Iowa, the ECB population typically has two generations per year (Mason et al.). The evaluated Bt events give complete control of both generations, but no data were collected on the first-generation population level or associated plant damage. As a result, any yield loss due to first-generation ECB larvae that occurred in the non-Bt hybrid would appear as a negative d. However, the analysis implies that average yield loss due to first-generation ECB larval damage is the same for each year the data were collected, which seems somewhat improbable. In addition to eliminating ECB, Bt corn also suppresses other corn pests such as the corn earworm, the black cutworm, the stalk borer, and the fall armyworm (Binning and Rice; Steffey et al.).[5] Again, any yield loss due to suppression of these pests would appear as a negative d. Unfortunately, the necessary pest population data or plant damage data to test either of these hypotheses were not collected.

The conventional and Bt hybrids compared in these experiments are genetically very similar, but not identical, and so they may have different yield potentials. As isoline hybrids, both the Bt and non-Bt hybrids share a recent common ancestor. However, each hybrid has been through one or more generations of separate breeding. Breeding for the Bt hybrid not only selected for the Bt gene, but also for superior agronomic traits. Breeding for the conventional hybrid also selected for superior agronomic traits, but because seed fertilization is a random gene transfer and mutations occur, the agronomic traits available for breeders to select from would not

[5] The evaluated Bt events also control or suppress the southwestern corn borer and the southern cornstalk borer, but these insects are not corn pests in Iowa where the data were collected.

be the same for both lines. As a result, the Bt hybrid may have a different yield potential than the conventional isoline hybrid. Similarly, instead of resulting from one or more generations of separate breeding, the Bt gene may be linked to favorable genes that enhance potential yield. In either case, both would appear as a negative d. Unfortunately, neither of these hypotheses can be tested with the available data, since the required information was not collected.

Our finding of a yield boost for Bt corn does not contradict other studies that find no evidence for a Bt corn yield drag (Graeber, Nafziger and Mies; Minor et al.; Nielsen; Willson). Following standard methods for analysis of experimental data, these studies used an ANOVA to test whether the mean yield for conventional and Bt hybrids statistically differed. These studies found no statistically significant difference in mean yield, or a statistically greater mean yield for Bt corn. However, these analyses did not control for ECB damage when testing, and so did not differentiate between yield differences due to elimination of damage by ECB (l) and differences due to changes yield potential (d). By controlling for ECB damage, we find that in addition to any increase in mean yield resulting from prevention of damage by second-generation ECB, Bt hybrids on average yield 1.65% more than non-Bt isoline hybrids.

Economic Analysis

To investigate the economic implications of these effects of Bt corn on the yield distribution, a model of per acre returns for a farmer planting Bt corn is developed based largely on the model of Mitchell et al. ECB larval population data and tunneling data from Bt field experiments are linked to the yield loss model estimated in the previous section. Following published studies, an independent distribution is used for potential yield. Because analytical solutions do not exist for the empirical model, simulation methods are used to obtain results for the economic analysis.

Dry weather (no rainfall, low humidity) during the ECB mating period and excessive rainfall at larval hatch can greatly reduce ECB populations (Mason et al.). Cumulative weather over the season determines corn yield, but these acute events during critical periods for ECB have little impact on yield, so that empirically little correlation exists between potential yield and ECB populations (Showers et al.). Thus potential yield is assumed to be uncorrelated with the ECB larval population, tunneling, and proportional damage, an assumption consistent with other analyses (Hyde et al. 1999, 2003; Mitchell et al.; Hurley, Mitchell, and Rice). Similarly, given the paucity of data, potential yield is assumed to be uncorrelated with the effects of Bt corn on yield that are unrelated to ECB control and so captured by d.

ECB Larval Population and Tunneling

The model of Mitchell et al. is used for the unconditional distribution of the second-generation ECB larval population per plant and the conditional distribution of stalk tunneling by second-generation ECB larvae. They used state average ECB larval population data for Illinois, Minnesota, and Wisconsin and county average data for Boone County, Iowa and Hall County, Nebraska to estimate unconditional lognormal distributions for each location. A lognormal distribution is used because larval populations cannot be negative. Consistent with other empirical studies (Chiang and Hodson; Chiang et al.; Showers et al.), time trends were insignificant and removed and no significant autocorrelation existed among the errors. Table 1 in Mitchell et al. reports the estimated mean and coefficient of variation of the per plant second-generation ECB larval population for each location used for this analysis.

Following Mitchell et al., tunneling was linked to the second–generation ECB population using field trial data from nine states. After testing several models for average tunneling (cm/plant) as a function of the average larval population, their final model is a lognormal distribution for tunneling, with a conditional mean of $a_1 n + a_2 \sqrt{n}$ and a conditional standard deviation of $b_0 + b_1 n$, where n is the average ECB population per plant and the remaining variables are parameters to estimate. They report maximum likelihood estimates of a_1 = 2.56, a_2 = 5.65, b_0 = 3.40, and b_1 = 1.73 (all with p-values less than 0.001), and an R-squared of 0.822.

Potential Yield

A beta density is used for the distribution of potential yield, a common assumption for crop yields (Goodwin and Ker review several examples). The beta density has four parameters: two shape parameters *n* and *w* and the minimum and maximum. The mean in each location is the average of the state or county average yield (bu/ac) for 1999-2001 (USDA-NASS 2002). Dryland averages are 147.7, 141.7, 134.0, and 154.7 in Illinois, Minnesota, Wisconsin, and Boone County, IA. The irrigated average is 161.3 in Hall County, NE. So that the mean yield for non-Bt corn matches these observed averages, mean potential yield is adjusted to equal $\bar{y}/(1 - \mathrm{E}[l])$ when the analysis only includes the effects of Bt corn on yield due to ECB control and $\bar{y}/(1 - \mathrm{E}[l] + \mathrm{E}[d])$ when the analysis also includes the effects of Bt corn on yield beyond ECB control. E[·] is the expectations operator and $\bar{y}$ is the state or county average yield.

Following data from crop insurance studies (Coble, Heifner, and Zuniga; Hennessy, Babcock, and Hayes), the coefficient of variation for potential yield is set at 30% for dryland corn and 15% for irrigated corn as reasonable assumptions concerning field-level yield variability. Following Babcock, Hart, and Hayes, the minimum potential yield for each location is zero and the maximum is the mean plus two standard deviations. The beta density shape parameters *n* and *w* consistent with these assumptions are *n* = 3.542 and *w* = 2.125 for the dryland locations and *n* = 9.487 and *w* = 2.846 for the irrigated location.

Yield Loss

The yield loss parameters reported in table 3 are used for determining harvested yield for conventional and Bt corn. Yield loss due to ECB is $l = at$ and the effect of Bt corn on yield beyond ECB control is captured by d. When the analysis only includes the effects of ECB control on yield, a has a normal distribution with a mean and standard error as reported in table 3, so that conventional yield is $y_0 = y(1 - at)$ and Bt yield is $y_1 = y$. When the analysis includes both the effect of ECB control and the yield boost implied by d, again $l = at$, but a and d have a joint normal distribution with means and standard deviations as reported in table 3 and a covariance of 3.31 x 10^{-6} from the estimated variance-covariance matrix, so that conventional yield is again $y_0 = y(1 - at)$ and Bt yield is $y_1 = y(1 - d)$.

For this model, tunneling t is strictly positive, so that $l = at$ has the same sign as a. For a normal random variable with mean and standard deviation as reported in table 3 for a, the probability that a is negative is quite small (1.024 x 10^{-7}). A small probability also exists that the realized l exceeds one, which is technically impossible. Therefore, simulations censor proportional yield loss l at 1.0. The probability that this censoring occurs cannot be calculated analytically for the empirical model when tunneling is random, but the fact that it was imposed six times in 1.25 million simulated random draws is evidence that its magnitude is small.

Farmer Returns and Preferences

To evaluate changes in the distribution of harvested yield when planting Bt corn, a model of farmer returns and a utility function are specified. Returns ($/ac) are $p_0 = py_0 - C$ for conventional corn and $p_1 = py_1 - C - T$ for Bt corn, where p is the price of corn ($/bu), C is the cost of production (\$/ac), and T is the additional cost (\$/ac) for Bt corn usually associated with the technology fee.

To maintain focus on yield risk, the analysis uses a non-random price of p = \$2.00/bu, a non-random cost of production C, and disregards all other sources of income and wealth. A negative-exponential utility is used so that wealth effects can be ignored. As a result, the cost of production does not affect the willingness to pay for Bt corn, as long as the cost is non-random and independent of yield. Following Babcock, Choi, and Feinerman, the coefficient of absolute risk aversion is chosen so that the implied risk premium is a reasonable percentage of the standard deviation of per acre returns. For each location, the average of the standard deviation of returns for conventional and Bt corn was first calculated with and without the yield effects from d. The coefficient of absolute risk aversion for a risk premium that is 20% and 40% of this standard deviation for each location was calculated using the method of Babcock, Choi, and Feinerman. With negative-exponential utility, the willingness to pay for Bt corn (\$/ac) is the difference in certainty equivalents with and without Bt corn and this willingness to pay can be directly compared to the technology fee T.

Simulations

The specified model for the relationship between yield loss, ECB tunneling, and the ECB population is a hierarchical model. A hierarchical model expresses a complex process as a series of linked conditional and marginal distributions (Casella and Berger, pp. 162-168). The parameters of one distribution depend on another random variable with its own parameters, and these parameters may also depend on another random variable, and so on, until reaching a final unconditional distribution. For the empirical model here, the first conditional distribution in the hierarchy is loss conditional on tunneling. Tunneling then has a conditional distribution depending on the ECB larval population, and finally the ECB larval population is unconditionally distributed. Other empirical analyses have successfully applied hierarchical methods (Babcock and Blackmer; Hurley, Mitchell, and Rice; Mitchell, Gray and Steffey).

Closed form expressions for unconditional distributions and their moments for conditional random variables in the hierarchy commonly do not exist, so that simulation methods are needed (Gelfand and Smith). For this model, analytical problems arise when deriving the unconditional distribution for proportional loss and its moments. As a result, Monte Carlo integration is used to solve integrals numerically (Greene, pp. 192-197). A C++ program used algorithms reported in Press et al. to draw the required random variables. Experimentation indicated that 250,000 draws from each distribution were sufficient for estimates to stabilize.

Yield Loss from Second-Generation ECB

Table 3 reports the estimated properties of the distribution of proportional yield loss l for each location. The expected yield loss due to ECB damage ranges 2.7-6.2%, which is comparable to, but slightly lower than, Calvin's empirically derived estimate of 6.4% as the average annual U.S. yield loss due to ECB. As expected, average losses are larger in locations with higher average ECB larval populations.

The relatively large standard deviation and the wide range between the 2.5% and 97.5% quantiles at each location imply that considerable variability exists in the yield loss actually realized. Consequently, substantial probability exists for actual losses in a specific year on a specific field to be large in Wisconsin and small in Nebraska. For example, the Monte Carlo estimated probability that losses exceed 4% in Wisconsin is 21.3% and the probability that losses are less than 3% in Hall County, NE is 27.5%. As a result, though the yield benefit from controlling ECB may on average be substantial, the actual yield gain realized for a specific field in any given year is quite variable. Indeed, aggregate analyses find that for many farmers, the *ex post* realized benefits from Bt corn did not exceed the costs in about half the years since commercialization (Carpenter and Gianessi; Benbrook 2001).

Bt Corn Yield Variance

Table 4 reports the changes in the mean and variance of harvested yield when switching from conventional to Bt corn. To highlight the two effects, separate results are reported for changes with just the effect of ECB control alone and with both the effects of ECB control and the yield boost implied by d. With just the effect of ECB control, Bt corn increases mean yield on average 3.6-10.0 bu/ac (2.8-6.6%). Adding in the effect of the yield boost implied by d increases mean yield an additional 1.65%, for a total increase in mean yield of about 5.9-12.7 bu/ac (4.5-8.4%). Comparing results with and without the yield boost indicates that ECB control generates around 60-80% of the increase in mean yield from planting Bt corn.

As a result of controlling ECB, Bt corn increases the variance of yield 3.4-7.9% for the systems analyzed. When the effect of the yield boost represented by d is also included, the total increase in yield variance ranges 7.2-11.6%. This finding that Bt corn increases the variance of harvested yield by eliminating ECB damage is consistent with the findings of Hurley and Babcock concerning Bt corn and with other conceptual and empirical analyses of pest control (Feder; Horowitz and Lichtenberg (1993,1994); Pannell). With proportional yield loss, when potential yield is high (low), the total yield lost is high (low) as well, so that pest damage tends to decrease yield variance. By eliminating ECB damage, Bt corn removes this variance dampening effect of pest damage, so that the variance of yield increases. However, Horowitz and Lichtenberg (1994, p.86) suggest that in irrigated systems pesticides are likely to be variance reducing, since pest damages are the major source of uncertainty. Consequently, farmers with low yield variability, whatever the cause, are likely to reduce the variance of harvested yield by planting Bt corn, or experience smaller variance increases. We find that this is indeed the case for the irrigated example when the effects of the yield boost *d* are not included—Hall County, NE has the smallest variance increase.

Our results concerning the impact of Bt corn on the variance of harvested variance are contrary to those reported by Hyde et al. (1999). ECB population data for Indiana were not available to replicate their analysis with our model. However, using the probabilities and yields reported by Hyde et al. (1999), their analysis uses a coefficient of variation of 14.6% for potential yield, which is much lower than for our dryland systems, but comparable to our irrigated system. Following the logic of Horowitz and Lichtenberg, since pest damages in this system are the major source of uncertainty, pesticides such as Bt corn are likely to be variance reducing as Hyde et al. (1999) find.

Care should be taken before interpreting the variance-increasing yield effect as empirical support for the notion that Bt corn is risk increasing or that assessments of the value of Bt corn to risk averse farmers should be reduced because of increased risk. Hurley, Mitchell, and Rice find that conclusions concerning the risk effects of Bt corn depend on the price of Bt corn and must carefully distinguish between the risk premium and the marginal risk premium for Bt corn. Furthermore, the analysis here holds a farmer's total corn acreage constant, but Hurley, Mitchell, and Rice find that corn acreage changes as a result of Bt corn adoption are also important for determining the risk effects of Bt corn.

Farmer Willingness to Pay for Bt Corn

Table 5 reports the willingness to pay (WTP) for Bt corn at different levels of risk aversion. A technology fee is not included, but because preferences exhibit constant absolute risk aversion, the WTP with any technology fee is simply the reported WTP minus the non-random technology fee. The technology fee for Bt corn is currently around $5-10/ac, but can vary beyond this range depending on a farmer's planting density and the supply and demand conditions for the specific hybrid (Benbrook 2001). Also, other costs associated with planting Bt corn not accounted for in this analysis include the cost of planting structured refuge and segregation costs (Mason et al.).

Assuming a total additional cost of $10/ac for Bt corn, the results in table 6 indicate that, with only the yield effects of ECB control, at low levels of risk aversion the WTP for Bt corn is positive only for the irrigated Hall County, NE example and slightly so for the Illinois and Boone County, IA examples. However, with the added Bt corn yield boost implied by d, the WTP for Bt corn with a cost of $10/ac is positive for all examples, except for the highly risk averse case in Wisconsin. These results imply that the yield boost, whatever its source, is an important component of the value of Bt corn. Comparing results with and without the yield boost indicates that the yield boost constitutes around 20-40% of the WTP for Bt corn. Only in locations with consistently high ECB pressure are the yield effects from controlling second-generation ECB sufficient by themselves for Bt corn to be cost effective for farmers.

Table 5 also shows that the WTP for Bt corn decreases as risk aversion increases. This result occurs because Bt corn generally increases the variance of harvested yield. For the dryland examples, the increased variance decreases the value of Bt corn 10-25% depending on the location and the level of risk aversion. For the irrigated example, risk aversion decreases the WTP for Bt corn much less (2.5-10.5%), since the variance increase is much smaller. In terms of percentage change in the WTP, the yield boost has little effect on the impact of risk aversion on the WTP for Bt corn. This result occurs because the increase in the mean yield offsets the decrease in the WTP due to the increased variance of harvested yield.

Implications of a Bt Corn Yield Boost

The yield boost in our analysis is an essential component in order for farmer willingness to pay for Bt corn to exceed the typical price, but the source of this yield boost remains unclear. Regardless of its source, this yield boost has implications for economic assessments of the value of Bt corn to farmers. If this boost is from control of first-generation ECB, then assessments should include this control benefit for Bt corn, as do Hyde et al. (1999, 2003) and Benbrook (2001). Results reported here incorporating the effects of d implicitly include these benefits, if d does indeed capture the yield benefit from control of first-generation ECB. However, the yield boost we identify may be due to suppression of secondary pests, the result of differential breeding, or genetic linkages. If assessments finding that Bt corn is not profitable for many farmers in many years (e.g., Carpenter and Gianessi; Benbrook 2001; Hyde et al. 1999; Fernadez-Cornejo and McBride) were to increase mean yield for Bt corn as much as our analysis indicates to account for this yield boost, these assessments could change to become more consistent with current adoption behavior.

Alternatively, if the yield boost results from differential breeding for Bt hybrids relative to conventional hybrids, it may be evidence that seed companies owned by biotechnology firms are expending fewer resources to maintain their non-Bt hybrids. If indeed this is the case, it seems likely that the magnitude of this yield boost will increase over time. The eventual outcome of this process would be a packaging of both technologies by the biotechnology-seed companies, so that farmers wanting to buy hybrids with the best agronomic traits would have to buy these hybrids with the Bt trait, whether they wanted the Bt trait or not. However, this technology packaging could create a market niche for seed companies willing to continue improving non-Bt hybrids, which could partially reverse the consolidation of the seedcorn industry that occurred in the 1990's as a result of biotechnology developments.

Finally, all the hypothesized sources of the yield boost may contribute to the identified yield boost and 1.65% is their net effect for the data analyzed. Additional research is needed to identify the source or sources of the yield boost and understand it economic implications.

Conclusion

Bt corn offers farmers a powerful tool for controlling European corn borer that generates value by changing the distribution of harvested yield. A statistical model was developed for analyzing Bt corn field trial data to separately identify the yield effects of Bt corn due to ECB control and due to other factors such as yield drag, suppression of other insect pests, and genetic linkages. To better understand the economic implications of these effects, an empirical model weighed the benefits from ECB control against the costs and/or benefits of these other factors and changes in the variance of harvested yield.

The analysis found that as a result of controlling ECB, Bt corn increased mean yield 2.8-6.6%. No evidence for a Bt corn yield drag was found, but rather support for the existence of a 1.65% yield boost that occurs for all three Bt events evaluated, regardless of the ECB damage prevented by Bt corn. The source of this yield boost remains unclear, but various hypotheses were proposed, including control of first-generation ECB, secondary pest suppression, differential hybrid breeding, and genetic linkages. The analysis also found that Bt corn increased the variance of harvested yield 3.5-7.9% as a result of controlling ECB. Beyond these variance effects from controlling ECB, Bt corn yield boost increased the variance of harvested yield by an additional 3.5-3.7%.

A model of farmer returns and preferences was used to estimate the economic significance of these results. Because Bt corn increased the variance of harvested yield, risk aversion decreased the value of Bt corn 10-25% from the risk neutral value. Without the yield boost, the benefit of Bt corn from controlling ECB exceeded $10/ac (an estimate of the typical cost of Bt corn) only for locations where ECB populations were consistently high (Nebraska and Illinois). However, once the yield boost was included, the benefit of Bt corn exceeded the cost for cases we evaluated, except for the case of a highly risk averse farmer in locations where ECB populations and potential yields were low (Wisconsin). These results highlight the importance of the yield boost as a source of value for Bt corn and another factor encouraging adoption. The analysis found that the yield boost constitutes 20-40% of the farmer willingness to pay for Bt corn and is crucial to making Bt corn cost effective in locations with moderate to low ECB populations.

Overall, the analysis indicates that Bt corn can generate substantial economic returns for many farmers by increasing their average yield. However, this increase in average yield must be weighed against the cost due to an increase in yield variance that is likely to occur for many farmers. Furthermore, though on average Bt corn generates substantial economic returns for many farmers, considerable variability exists in the realized benefit. As a result, for a particular farmer in a particular year, the actual benefit realized at the end of the season may not offset the added cost of planting Bt corn.

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Table 1. Event-year specific estimates (standard errors in parentheses) of the second-generation European corn borer (ECB) damage effect from stalk tunneling and the non ECB effect on the proportional yield difference between conventional and Bt corn.

Event-Year	Observations	ECB Damage Effect *a*	Non-ECB Effect *d*	Standard Deviation *t*
MON810, 1997	43	0.0064*** (0.0021)	-0.0274* (0.0161)	0.0604*** (0.0065)
MON810, 1998	37	0.0068 (0.0044)	-0.0185* (0.0099)	0.0411*** (0.0048)
MON810, 1999	10	0.0101** (0.0048)	-0.0014 (0.0108)	0.0252*** (0.0056)
DBT418, 1997	14	0.0042*** (0.0014)	-0.0133 (0.0129)	0.0276*** (0.0052)
Bt11, 1998	26	0.0065 (0.0167)	-0.0077 (0.0267)	0.0853*** (0.0118)

* Significant at the 10% level of significance.
** Significant at the 5% level of significance.
*** Significant at the 1% level of significance.

Table 2. Effect of Bt corn on the proportional yield difference between conventional and Bt corn due to second-generation European corn borer control (ECB Effect) and other factors (Non ECB Effect).

Parameter	Estimate	Standard Error	P-Value
ECB Effect *a*	0.00520	0.00100	<0.001
Non-ECB Effect *d*	-0.0165	0.00549	0.003
Standard Deviation *t*			
MON810, 1997	0.0630	0.00697	<0.001
MON810, 1998	0.0414	0.00484	<0.001
MON810, 1999	0.0275	0.00631	<0.001
DBT418, 1997	0.0297	0.00618	<0.001
Bt11, 1998	0.0856	0.01187	<0.001

Table 3. Monte Carlo estimates of the statistical properties of the proportional yield loss due to second-generation European corn borer damage.

Location	Mean	Standard Deviation	------ Quantiles ------ 2.5%	97.5%
Illinois	0.046	0.038	0.006	0.145
Minnesota	0.035	0.034	0.003	0.123
Wisconsin	0.027	0.030	0.001	0.104
Boone County, IA	0.036	0.034	0.003	0.126
Hall County, NE	0.062	0.044	0.012	0.175

Table 4. Change in the mean and variance of harvested yield when switching from conventional to Bt corn.

	ECB Control Only		ECB Control and Yield Boost	
Location	Change in Yield Mean	Change in Yield Variance	Change in Yield Mean	Change in Yield Variance
Illinois	6.9 (4.9%)	142.7 (7.9%)	9.3 (6.6%)	209.8 (11.6%)
Minnesota	5.0 (3.6%)	100.0 (5.9%)	7.3 (5.3%)	161.1 (9.4%)
Wisconsin	3.6 (2.8%)	69.8 (4.5%)	5.9 (4.5%)	124.9 (8.1%)
Boone County, IA	5.6 (3.8%)	123.7 (6.1%)	8.1 (5.5%)	194.8 (9.6%)
Hall County, NE	10.0 (6.6%)	19.4 (3.4%)	12.7 (8.4%)	40.8 (7.2%)

Table 5. Willingness to pay ($/ac) for Bt corn relative to conventional corn with different levels of risk aversion.

	ECB Control Only			ECB Control and Yield Boost		
	-------- Risk Premium --------			-------- Risk Premium --------		
Location	0%	20%	40%	0%	20%	40%
Illinois	13.72	12.23	10.28	18.62	16.47	13.73
Minnesota	9.96	8.88	7.45	14.62	12.91	10.75
Wisconsin	7.30	6.50	5.46	11.71	10.32	8.56
Boone County, IA	11.21	9.99	8.39	16.29	14.40	12.01
Hall County, NE	20.05	19.54	18.42	25.36	24.44	22.72