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The Value of Bt Corn in Southwest Kansas: A Monte Carlo Simulation Approach

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While most Corn Belt farmers consider planting Bt corn to control European corn borer, southwestern Kansas farmers must also take into account an array of other insect pests, including corn rootworm, spider mites, and southwestern corn borer. This research uses a decision analysis framework to estimate the expected economic value of Bt corn in southwest Kansas. Mean per acre Bt values ranged from $12.49 to $34.60, well above the technology fee assumed to be $14 per unit, or $5.25 per acre at a seeding rate of 30,000 seeds per acre. The minimum value over all scenarios was $8.69 per acre. Using Monte Carlo simulation, it was shown that European and southwestern corn borer infestation probabilities, expected corn price, and expected pest-free yields are important determinants of the value of Bt corn.

Key words: Bt corn, decision analysis, European corn borer, integrated pest management, Monte Carlo simulation, southwestern corn borer

Introduction

The European corn borer (ECB), *Ostrinia nubilalis* (Hübner), is a major corn insect pest. Estimates of ECB damage in the United States exceed $1 billion annually (Russnogle). In 1996, corn genetically engineered to control ECB, as well as some other corn insect pests, was commercially introduced. The genetic makeup of these plants has been modified so that the corn now produces its own *Bacillus thuringiensis* kurstaki (Bt) proteins, which are toxic to ECB and certain other insect pests.

Most insecticides used across the Corn Belt are about 80% effective in controlling ECB. Chemical insecticides such as bifenthrin (Capture®) may be significantly more effective, with an efficacy in the range of 90–95%. However, YieldGard® Bt corn provides nearly 100% effective control of ECB throughout the entire growing season (Ostlie, Hutchison, and Hellmich). Based on U.S. Department of Agriculture/National Agricultural Statistics Service (USDA/NASS) data, in 2001, about 16% of U.S. corn acres were planted to Bt corn, down from 18% in 2000. In comparison, 25% of Kansas corn acres were planted to Bt corn in both 2000 and 2001.

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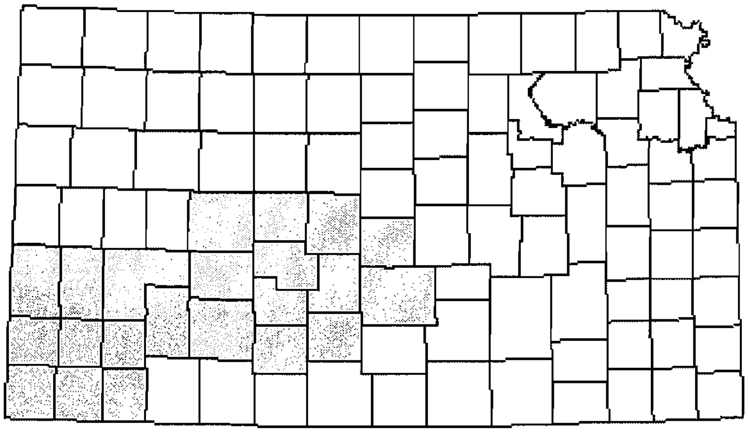

Figure 1. Southwest Kansas study region

The southwestern region of Kansas differs a great deal from the remainder of the Corn Belt. While most Corn Belt farmers would consider planting Bt corn to control only ECB, southwest Kansas farmers must consider a broader array of insect pests. Pressure from southwestern corn borer (SWCB), *Diatraea grandiosella* (Dyar), and spider mites, *Tetranychidae spp.*, must be accounted for when making the decision whether or not to plant Bt corn.

The primary objective of this research is to estimate the value of Bt corn to growers in the southwest Kansas region (as shown in figure 1). However, despite this specific geographic focus, the analysis may be applicable to a much larger geographic area.

Bt Corn

Using the tools of genetic engineering, scientists have inserted a gene from Bt, a naturally occurring soil bacterium, into the corn's deoxyribonucleic acid (DNA). The genetically modified corn plant produces a protein that destroys cells in some insects' guts, causing the insects to cease eating and eventually to die (Ostlie, Hutchison, and Hellmich). Of the types of Bt corn available, two are sold under the brand name YieldGard® (BT11 and MON810, developed by Northrup King/Novartis Seeds/Syngenta and Monsanto, respectively). It is assumed these represent the most prevalent type of Bt corn planted in the southwest Kansas region, based on discussion with seed salespeople and crop scouts in the region. Thus, YieldGard® Bt corn was selected for analysis in this study. The YieldGard® technology has been approved by regulatory agencies in the United States, the European Union, and Japan.

Previous Analyses of Farm-Level Bt Corn Benefits

While the literature contains several examples of farm-level studies of genetically modified crops, few studies have focused on the farm-level economic effects of Bt corn adoption. Some have analyzed pest management implications (e.g., Hurley, Babcock, and Hellmich; Hyde et al. 2000, 2001). Others have examined costs of segregation of Bt and non-Bt corn (e.g., Bullock, Desquilbet, and Nitsi).

This analysis builds most directly from the work of Hyde et al. (1999), which provided an analysis of the value of Bt corn in Indiana. Hyde et al. used a decision analysis approach, similar to that adopted in this study. However, they did not account for uncertainty in the input variables, which are taken into account here via the simulation approach employed. Hyde et al. reported Bt corn values between $4.44 and $5.19 per acre, depending upon the assumed level of risk aversion, when the overall probability of ECB infestation is 25%. These values were shown to increase to between $7.50 and $8.58 when the probability of ECB infestation is 40% in a given year.

The current study differs from Hyde et al.'s earlier work in two distinct ways. First, Monte Carlo simulation is employed to incorporate uncertainty in key input variables (e.g., yield, price, yield losses from insects, etc.). Second, this investigation focuses on a region with very different pest population dynamics than those faced by Indiana farmers. While Indiana has relatively low pest pressure, southwest Kansas farmers face more frequent infestations from a variety of different insect pests.

Relevant Insect Pests in Southwest Kansas

First-generation European corn borers attack the plant relatively early in the growth process and feed on leaves before tunneling into the corn stalk, destroying pathways for plant nutrient movement in the xylem and phloem. Second-generation ECB feed on the ear and ear shanks before tunneling into the plant. Decreased yield due to the destruction of nutrient pathways is known as "physiological damage." Ear drop due to ECB feeding on ear shanks and lodging due to stalk tunneling is classified as "mechanical yield damage."

The southwestern corn borer causes the same types of damage. However, unlike ECB, second-generation SWCB often "girdle" the corn plant, chewing a complete ring around the inside of the stalk a few inches above ground level, making it susceptible to breaking in strong winds (Sloderbeck, Higgins, and Buschman). This damage can be a more significant source of yield loss than ECB feeding.

Spider mites damage the corn plant by removing cell contents from the leaves (Sloderbeck, Buschman, and Higgins). Bt toxin does not directly affect spider mites. However, non-Bt corn fields are often sprayed for ECB or SWCB with insecticides which can kill other insects that prey on spider mites. Thus, spider mites may be controlled indirectly in Bt corn. While the increase in populations of beneficial insects in Bt corn may be an important secondary effect, it is not accounted for in this analysis.

Corn rootworm (CRW), *Diabrotica spp.*, control differs in Bt and non-Bt corn. In non-Bt corn, it is typically controlled with an adulticide program, in which mature CRW are sprayed sometime in early to mid-August. This spray also affects the European and southwestern corn borers and spider mites. In Bt corn, a soil insecticide is typically applied at planting. There may be some carryover benefits from one year to the next with both a soil insecticide and an adulticide program. In the first year of a corn rootworm soil insecticide treatment, there should be reduced root damage and insect populations. With an adulticide program, the following year's root damage and insect populations may be decreased. Here, we assume CRW control is applied every year, and the efficacy of control is the same for both a soil insecticide and an adulticide (Buschman; Sloderbeck). Hence, our model simplifies the dynamic nature of CRW control. Although control is about the same with each treatment program, their costs differ and must be reflected in the analysis.

Research Methodology and Data

A decision analysis framework was employed to estimate the value of Bt corn to farmers in the southwest Kansas region. The model analyzes one acre planted to either Bt corn or non-Bt corn. The problem is one of choice under uncertainty, where it is assumed the decision maker maximizes expected utility (see Raiffa or Varian for further theoretical discussion). Thus, the impact of risk aversion on the value of Bt corn can be estimated. In so doing, this analysis builds on earlier analyses of farmers' choices made under uncertain conditions. This theory has been applied to agricultural problems by several researchers (see Anderson, Dillon, and Hardaker for a review of literature on how farmers deal with risk) and is the foundation for the decision analysis model developed for this investigation.

The decision analysis approach is appropriate for analyzing problems of choice under uncertainty when each of the decision sets and probability distributions faced by the decision maker is discrete (Pratt, Raiffa, and Schlaifer). For the present problem, the decision set may be viewed as discrete, but some of the probability distributions are continuous. However, these are approximated as discrete distributions due to a lack of field data needed to properly specify a continuous distribution.

The current study extends the research of Hyde et al. (1999) by using Monte Carlo simulation techniques (Law and Kelton; Winston) to analyze the sensitivity of the estimated Bt value to certain underlying probability distributions, but not those which do not enter the model directly. Thus, this is an instance of systematic sensitivity analysis of the sort described in Wigle, and in Harrison and Vinod. This approach yields a distribution of breakeven Bt values, rather than point estimates, that are based on other point estimates of prices, potential pest-free yield, and other underlying variables.

Structure of the Decision Analysis Model

The development of any decision analysis model requires four steps (Raiffa). First, all possible events—choices to be made and/or random events—must be identified. Second, a timeline showing the sequence of these events must be developed. Third, the decision maker must assign utility values to the potential outcomes. Finally, each outcome must be assigned a probability of occurrence.

A timeline showing the relevant possible events in southwest Kansas identifies the first event, forming the "root" of the decision tree, as the choice of seed (table 1). For this analysis, the farmer chooses between non-Bt corn and YieldGard® Bt corn, henceforth referred to simply as Bt corn. Implied in this model is the assumption that the farmer has made the decision to plant corn to the acres in question. Indeed, the farmer may choose whether or not to plant corn or some other crop, or more generally, some mixture of crops. However, it is assumed this decision is made prior to the decision of which type of corn to plant.

The second event in the timeline is the realization of a random planting date. The planting date is random mainly due to weather events, which are treated as uncertain. As noted in the description of the data below, the outcome of this random event is important for two reasons. First, the level of damage from insect infestations is a function of the stage of growth of the corn plant at the time of infestation, which is, in turn, a function of the planting date. Second, corn planted after a particular period tends to yield less than corn planted in a more timely fashion.

Table 1. Model Timeline of Important Events

	EVENTS			
Date	Farmer Action	ECB Biology	SWCB Biology	Mite Biology
Winter	seed choice			
April 1–June 15	planting			
June 15[a]		1st generation		
June 15–28	spray[b]			
June 28[a]			1st generation	
August 4[a]		2nd generation		
August 5–11	spray[b]			infestation[c]
August 11[a]			2nd generation	
Fall	harvest			

Note: The model timeline is attributed to expert opinion of entomologists in southwest Kansas (Buschman; Sloderbeck; Higgins).

[a] These dates are four days after the peak flight date, provided by Buschman, to represent the amount of time necessary for larvae to emerge following peak flight.

[b] Decisions to spray occur when the conditional net expected benefit of spraying is positive. Thus, spraying does not occur without infestation, and will occur only if the expected benefits of spraying for an infestation outweigh the costs of spraying. As modeled, the farmer knows all that has happened leading up to the decision, including a realization of ECB infestation. The farmer makes the spray decision based upon this knowledge and the conditional distribution of infestations by other insects in that particular generation.

[c] It is assumed mite infestation occurs sometime around second-generation corn borer pressure. This assumption is based on the understanding that spraying for spider mites often occurs at this time and that Capture® has a relatively long residual period (Buschman; Sloderbeck).

As shown in table 1, the period from June 15 to June 28 is when first-generation European and southwestern corn borer infestations may occur. In non-Bt corn, the farmer may choose to spray for first-generation insects. (It is assumed there is no benefit to spraying for ECB or SWCB in Bt corn.) Often, the farmer will choose a product such as Pounce®, Lorsban®, or Warrior® for first-generation insecticide applications (Buschman; Sloderbeck). As modeled, the farmer makes the decision based upon the realized planting date, realized ECB infestation level, and the conditional distribution of SWCB infestation. Note that first-generation insects only infest early planted corn (April 1 through April 30).

Next in the timeline is a series of potential infestations, starting with second-generation ECB on August 4 and concluding with second-generation SWCB on August 11. Spider mite infestation is modeled as occurring sometime between the corn borer infestations. As modeled, farmers spray once for all of these insects. In practice, farmers may make two less-potent applications, which would increase spray costs. The lower spraying costs based on a single application are used here. This one-spray assumption may bias the value of Bt corn downward.

In Bt corn, an insecticide, typically Capture®, is applied to control spider mites. In non-Bt corn, the same product is sprayed at a high level of active ingredient following ECB infestation. When sprayed at high doses, the application may have a residual effect of up to three weeks, thereby controlling spider mites and SWCB as well. This spray may also constitute a corn rootworm adulticide program. Thus, the single-spray program is designed to control up to four insect pests: the European corn borer, the southwestern corn borer, spider mites, and the adult corn rootworm.

At the time the spraying decision is made, the farmer knows the realized planting date, the realized first-generation ECB and SWCB infestation levels, whether or not first-generation insects were sprayed, and the realized level of second-generation ECB infestation. In reality, the farmer may spray before or after realizing a spider mite infestation. In the simulation model, however, the decision to spray for ECB, SWCB, and spider mites in non-Bt corn is based upon the realized planting date, realized first-generation ECB and SWCB infestation levels, whether or not first-generation insects were sprayed, the realized level of second-generation ECB infestation, and the conditional distributions of SWCB and spider mite infestation levels. Therefore, the spray decision in the model is made before SWCB and spider mite infestations occur, although the conditional distribution of infestations is a factor in the spraying decision.

At the end of the timeline, the farmer harvests the corn and realizes a particular yield and revenue outcome. The payoff associated with that outcome is equal to the revenue of the outcome, price times yield, minus any relevant cost. Only those costs that differ between Bt and non-Bt corn are included in the model, and corn price is assumed the same for both Bt and non-Bt varieties.

After calculating the payoff associated with each possible outcome conditional on the random and choice events, the results may be used to impute a value for the Bt trait in corn. Model solution begins at the conditional payoffs and proceeds backward through time toward the root. The first event moving backward through time is the random event of second-generation southwestern corn borer infestation. At that point, the model calculates the expected payoff associated with the random event. The expected payoff, $E(X)$, is simply the sum (over six possible realizations of SWCB pressure) of the products of payoffs, X_i, multiplied by associated probabilities, $P(X_i)$, or

$$E(X) = \sum_{i=1}^{6} X_i \times P(X_i).$$

Note that the payoff may be either net returns, in the case of a risk-neutral producer, or the utility of net returns, for a risk-averse producer.

The next event is a choice to spray for second-generation European and southwestern corn borers and spider mites. (To simplify the analysis, it is assumed the farmer treats for corn rootworm each year in both Bt and non-Bt corn.) The option with the greatest expected payoff from that point forward in time is selected. Hence, the decision is based upon the realization of second-generation ECB pressure and expectations of pressure from spider mites and second-generation SWCB. The probability of spider mite pressure is independent of corn borer infestation. The probability of spider mite infestation is 50% in either case. As modeled, the probability of SWCB pressure, given that ECB infestation occurs, is 100%—i.e., either both occur in a given year or neither does. While this is not perfectly reflective of real-world observation, it is a good approximation (Buschman; Sloderbeck).

The solution process continues toward the root in this manner. At each decision point, the option with the greatest expected payoff from that point forward in time is selected. At each random event, the model calculates the expected payoff, assuming the decision maker behaves as an expected payoff maximizer from that time forward.

Upon reaching the two initial branches, one for the choice to plant Bt corn and one for the choice to plant non-Bt corn, an expected payoff for each seed type has been calculated based on the assumption that the optimal conditional spraying pattern is followed. If the payoffs are expressed as net returns, then the difference between these expected payoffs represents the maximum amount the risk-neutral farmer should be willing to pay to plant Bt seed.

By introducing utility as a function of the payoffs, the impact of risk-averse behavior on the estimated value of Bt corn can be estimated. This research employs a negative exponential utility function of wealth (Arrow), represented as $U(W) = -\exp(-\rho W)$. In this representation of utility (U), W is the value of the net return, exp is the exponential operator, and ρ is the coefficient of risk aversion. The negative exponential utility function exhibits constant absolute risk aversion (ARA, equal to ρ) and increasing relative risk aversion (RRA, equal to ρW). For this analysis, two levels of risk aversion are analyzed: risk neutral (RRA = 0) and highly risk averse (RRA = 5). This choice is based upon previous work showing RRA = 5 to be appropriate for farmers who are very averse to risk (Anderson, Dillon, and Hardaker). Model solution occurs in the same manner as before.

A simple example may aid the reader in understanding the solution process (figures 2–4). Suppose a farmer were choosing between Bt and non-Bt corn. First, the seed decision is made, forming the "root" of the tree. Second, the farmer realizes some level of insect infestation. The three possibilities are 0, 1, and 2 European corn borers per plant with yield losses of 0%, 5%, and 10%, respectively. If infestation occurs, the farmer must decide to spray or not. Given this information, the decision tree can be constructed (figure 2).

The tree shows six possible final outcomes, or "leaves," in this example. When choosing Bt corn, the level of infestation and related spraying choice are not relevant because the Bt is assumed to be fully effective against ECB damage. Thus, the farmer receives the associated weather-adjusted outcome with certainty. However, choosing non-Bt corn is much like choosing a lottery. The farmer may experience some level of infestation and then must choose to spray or not. The spraying choice is not relevant when a 0% infestation is realized. Therefore, the tree does not branch within the no-infestation subtree.

Suppose the farmer holds the following beliefs. First, yield will be 150 bushels per acre and corn price will be \$2.50 per bushel. Second, spraying costs \$15 per acre and is 70% effective against ECB damage. Finally, the probability of 0%, 5%, and 10% ECB damage is 60%, 20%, and 20%, respectively. These assumptions yield unique outcomes (figure 2), where the outcomes are calculated as the price multiplied by the realized yield (which is a function of insect damage and spraying) less any costs associated with spraying.

The solution process begins at the leaves and proceeds to the root. With infestation in non-Bt corn, the farmer must choose to spray or not. With an infestation of one ECB per plant, the risk-neutral farmer chooses not to spray because the payoff associated with not spraying (\$356.25) is greater than the payoff when spraying occurs (\$354.38). With a two ECB per plant infestation, the farmer will choose to spray because the payoff of spraying (\$348.75) is greater than the payoff of not spraying (\$337.50). With this choice, the decision tree can be pruned back to remove the suboptimal choices (figure 3).

The next step of the solution process involves a random event, ECB infestation. Thus, the expected value of the payoff must be calculated assuming the farmer behaves optimally at the time of the spraying choice, thereby maximizing expected payoff. The expected value of non-Bt corn is simply the sum of the payoffs given in figure 3 multiplied by the probability of those payoffs (figure 4):

$$(\$375.00 \times 0.6) + (\$356.25 \times 0.2) + (\$348.75 \times 0.2) = \$366.00.$$

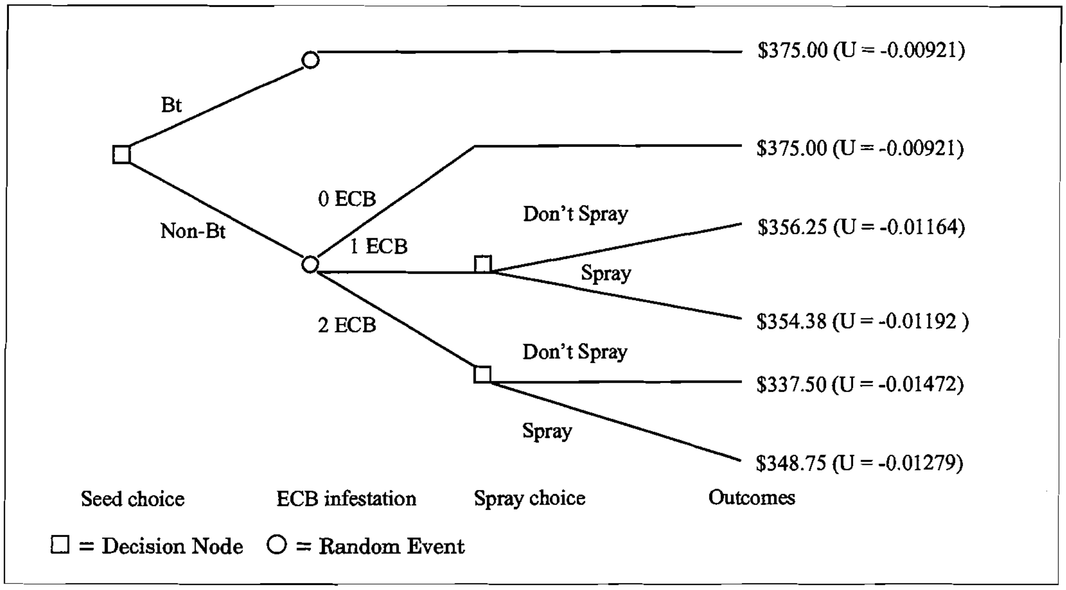

Figure 2. Example decision analysis problem: Decision tree tree with money and utility payoffs

Under these assumptions, the farmer should be willing to pay up to \$9 (i.e., \$375 – \$366) for the Bt corn. This is the difference in expected returns between Bt and non-Bt corn. An identical process could be used to analyze the value of the Bt trait to a risk-averse producer if the payoffs are expressed in utils, rather than dollars, and the final expected utility level is converted to dollars via a certainty equivalent (CE) calculation,

$$CE = \frac{-\ln\left[-E(U(w))\right]}{\rho},$$

for the negative exponential utility function. The ultimate choice would be based on the option with the greatest expected utility, and the value of the Bt trait would be based on the difference in the certainty equivalents.

Description of Data

To construct the decision analysis model, the steps suggested by Raiffa were followed. Table 1 shows all potential events in the form of a timeline, covering the first two steps in Raiffa's procedure. The third step is to assign utility values to the potential outcomes. This step requires calculation of the conditional payoffs. To do this, data on yield losses due to insect damage and costs of spraying were collected. European corn borer losses were specified based on those reported in Edwards, Foster, and Obermeyer, while southwestern corn borer losses and spraying costs were provided by Buschman and by Sloderbeck.

Because spraying is the best substitute for Bt corn to control corn borers, its cost must be included in the model. Recall also that corn rootworm control methods differ between Bt and non-Bt corn. Consequently, the costs of controlling CRW must be included as well. The cost of scouting for corn borers (both ECB and SWCB) is also included.

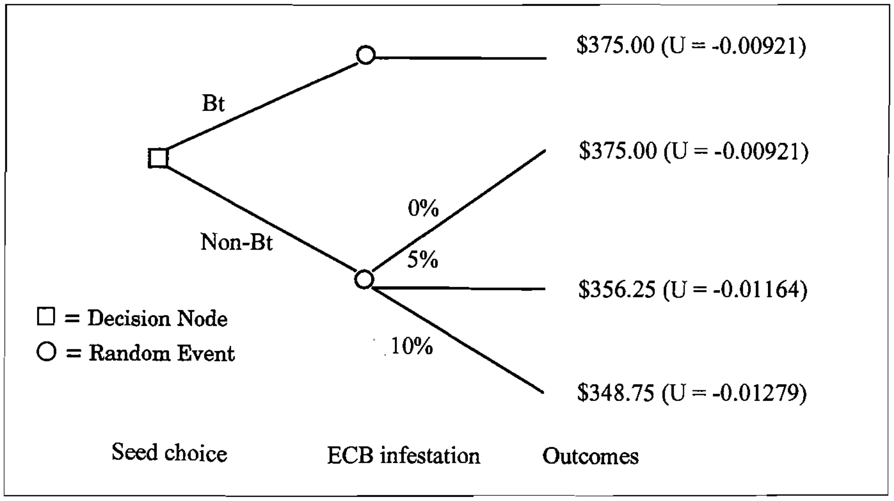

Figure 3. Example decision analysis problem: Step 1 of the solution

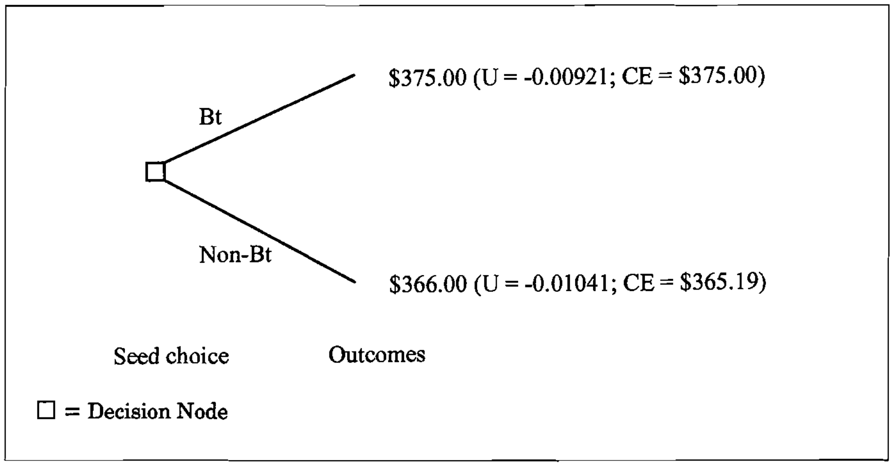

Figure 4. Example decision analysis problem: Step 2 of the solution

The cost of spraying differs by generation of corn borer (table 2). For first-generation infestations, it is assumed Warrior® is applied, if warranted, at a cost of $13 per acre. The efficacy of this application in controlling first-generation ECB and SWCB is assumed to have a triangular distribution of *TD*(50%, 70%, 90%), where 50%, 70%, and 90% indicate a minimum, most likely (mode), and maximum level of control (Buschman; Sloderbeck). For second-generation ECB and SWCB infestations, as well as spider mites, Capture® is applied to non-Bt corn at a total cost of $20 per acre, resulting in European corn borer control distributed as *TD*(60%, 80%, 95%), southwestern corn borer control distributed as *TD*(60%, 85%, 99%), and spider mite control distributed as *TD*(50%, 80%, 95%). The spraying of Capture® also controls corn rootworm at a cost of $10 per acre. (As mentioned above, we assume farmers spray for CRW each year in both Bt and non-Bt corn.)

Table 2. Costs and Effectiveness of Spraying Insecticides

Description	Base Cost[a] ($/acre)	Range[b] ($/acre)
Scouting for corn borers	1.50	0.75–1.50
First-generation insects: ▸ ECB and SWCB efficacy = *TD*(50%, 70%, 90%)[c]	13.00	6.50–13.00
Second-generation insects, and spider mites: ▸ ECB efficacy = *TD*(60%, 80%, 95%) ▸ SWCB efficacy = *TD*(60%, 85%, 99%) ▸ Spider mites efficacy = *TD*(50%, 80%, 95%)	20.00	10.00–20.00
Aerial insecticide for CRW control	10.00[d]	5.00–10.00
Soil insecticide for CRW control	17.00	8.50–17.00

Notes: Costs of spraying for corn borers includes $4 per acre for aerial application.

[a] Sources: Buschman; Sloderbeck.

[b] Base values are halved to analyze sensitivity of Bt value to costs associated with spraying.

[c] *TD* denotes a triangular distribution.

[d] Represents the portion of the cost of the adulticide program attributable to CRW control. This cost arises from increased use of Capture® with the adulticide program.

Total control cost in non-Bt corn, then, is $30 per acre when the farmer also sprays for ECB, SWCB, and spider mites. Hence, the expense of CRW control is incurred each year, while the $20 cost of controlling the other insects is only incurred when the model calculates that the expected benefits of spraying for those insects exceeds the cost. Even if the model indicates spraying is not optimal, the CRW spray may decrease yield damage from the relatively low population levels of the other insects. This would bias the value of Bt corn slightly upward. Also, the model chooses to spray non-Bt corn for ECB, SWCB, and spider mites together. In reality, some farmers may spray non-Bt corn if the spider mite population is high, even if ECB and SWCB infestations are low. This may also bias the valuation of the protection provided by Bt slightly upward.

With Bt corn, farmers are assumed to use a soil insecticide applied at planting to control corn rootworm (Buschman; Sloderbeck). Empirical observation in the southwest Kansas region shows farmers may be replacing soil insecticide programs in Bt corn with potentially less expensive adulticide programs (Sloderbeck). For these cases, the results here underestimate Bt corn values. The total cost of applying a soil insecticide, such as Counter®, is $17 per acre (compared with $10 per acre for the adulticide program used in non-Bt corn), and CRW control is assumed to be the same between the two programs. Rather than specify a distribution of insecticide costs, each of these prices was halved during sensitivity analysis to determine the impact of insecticide costs on Bt values. Spider mites may also be controlled in Bt corn at a cost of $15 per acre (Buschman; Sloderbeck).

It is also important to define several potential planting periods (table 3). Realized yield is a function of the planting date because fields planted later tend to yield less than fields planted in a timely manner (Buschman). In addition, yield damage from insects depends upon the growth stage of the corn at infestation, which is a function of planting date. Of these factors, insect damage is more important because, on average, over 80% of all corn planted in Kansas is done in a timely manner, before May 15 (USDA/NASS 1999). The probability distribution associated with the planting date

Table 3. Potential Corn Planting Periods with Associated Yield Losses and Probabilities Due to Delayed Planting (%)

Planting Period	Yield Loss[a]	Probability[b]	Planting Period	Yield Loss[a]	Probability[b]
April 1–15	0	6.7	May 16–31	15	14.2
April 16–30	0	35.6	After May 31	25	3.9
May 1–15	2	39.6			

[a] Sources: Buschman; Sloderbeck.

[b] Source: USDA/NASS (1999). These probabilities represent the average percentage of corn planted within each period in southwest Kansas.

reflects the average percentage of corn planted in the region within a given defined period over the years 1985 to 1998.

Estimates of potential yield damage from ECB and SWCB are also incorporated into the decision analysis model (tables 4 and 5). First, estimates of yield losses by growth stage of the corn plant were collected (table 4). Six growth stages are incorporated into the model: early whorl, late whorl, pre-tassel, pollen shed, blister, and dough. The base yield loss is the total damage from one ECB per plant or 0.1 to 0.2 SWCB per plant at a particular growth stage (Edwards, Foster, and Obermeyer; Buschman; Sloderbeck). Damage due to additional insects per plant is a direct function of the base loss (see footnote to table 4). Also, mechanical damage is a function of the total physiological loss (Lynch). Thus, total yield losses at a particular growth stage can be found by adding losses due to increased insect numbers and losses due to mechanical damage to the base yield loss.

The yield loss by stage of plant growth and number of insects per plant was specified as a triangular distribution with a mode equal to the total yield loss for that growth stage and number of insects. The minimum and maximum values were specified as one-half the total loss and twice the total loss, respectively.

Because infestations occur at specified dates in the model, they may occur at times other than the six growth stages identified above. In these instances, the yield loss value is calculated via linear interpolation for the nearest growth stages (table 5). Thus, yield damage is assumed to change in a linear fashion between growth stages.

The level of potential (pest-free) yield in irrigated corn was specified as a triangular distribution, *TD*(109.98, 159.23, 166.99) bushels per acre. For dryland corn, the specified triangular distribution is *TD*(91.99, 153.17, 165.36) bushels per acre. The minimum and maximum values correspond to the actual yields in southwest Kansas from 1982 to 2000 (USDA/NASS). The mode was selected so as to yield a distribution with mean equal to the actual mean over that period, which was 145.4 and 136.8 bushels per acre in irrigated and dryland fields, respectively. Corn prices were also specified as a triangular distribution, *TD*($1.68, $2.17, $3.29). Again, these reflect actual prices from 1982 to 2000, when the mean was $2.38. Finally, yield losses due to spider mites were specified as *TD*(0%, 5%, 20%) (Buschman; Sloderbeck).

Additional analysis was performed to determine the effect of increasing the variance of the input distributions. In those analyses, each of the triangular distributions was respecified as a uniform distribution with mean equal to that of the triangular distribution. Thus, where a triangular distribution is skewed to the right, we decrease the lower bound from the triangular distribution in specifying the uniform distribution.

Table 4. Physiological Yield Losses by Stage of Corn Plant Growth

			Other Losses	
Plant Growth State	Type of Borer	Base Yield Loss[a]	Other Borers[b]	Mechanical Damage[c]
Early Whorl	ECB	0.055	[see note below]	0.049
	SWCB	0.020	+0.03	0.049
Late Whorl	ECB	0.044	[see note below]	0.038
	SWCB	0.030	+0.04	0.038
Pre-Tassel	ECB	0.066	[see note below]	0.039
	SWCB	0.050	+0.06	0.039
Pollen Shed	ECB	0.044	[see note below]	0.128
	SWCB	0.030	+0.04	0.128
Blister	ECB	0.030	[see note below]	0.447
	SWCB	0.030	+0.04	0.447
Dough	ECB	0.020	[see note below]	0.447
	SWCB	0.030	+0.04	0.447

Note: The second ECB does half the damage of the first, the third does one-third as much damage. Thus, total damage for the third ECB is equal to the base yield loss plus one-half of the base plus one-third of the base.

[a] Figures represent one ECB per plant or 0.1 to 0.2 SWCB per plant.

[b] Sources: ECB data – Edwards, Foster, and Obermeyer; SWCB data – Buschman; Sloderbeck.

[c] Source: Lynch; figures represent percentages of total physiological loss.

Table 5. Equations for Interpolating Yield Losses by Planting Period, Type of Corn Borer, and Borer Generation

Planting Period	Type of Borer	First Generation	Second Generation
April 1–15	ECB	0.2 PS + 0.8 PT	D
	SWCB	0.5 B + 0.5 PS	D
April 16–30	ECB	(7/20) PT + (13/20) LW	D
	SWCB	PT	D
May 1–15	ECB	(5/9) LW + (4/9) EW	(13/15) B + (2/15) D
	SWCB	0.25 PT + 0.75 LW	0.6 D + 0.4 B
May 16–31	ECB	0.7 EW	0.4 PT + 0.6 PS
	SWCB	(7/18) LW + (11/18) EW	0.3 B + 0.7 PS
After May 31	ECB	0	0.35 LW + 0.65 PT
	SWCB	0.7 EW	PT

Notes: EW = early whorl, LW = late whorl, PT = pre-tassel, PS = pollen shed, B = blister, and D = dough.

Where a triangular distribution is skewed to the left, the maximum value is increased in the corresponding uniform distribution.

The final step is to apply probabilities to each of the outcomes (table 6). The data show a second-generation corn borer infestation is much more likely than a first-generation infestation. Also, if infestation occurs, it is relatively rare to realize high levels of insects—i.e., more than one European corn borer per plant or more than 0.4 southwestern corn borer per plant. Finally, results indicate, in three of four years, the farmer realizes some infestation of ECB, SWCB, or spider mites.

Table 6. Probabilities Associated with Insect Infestation

A. Probability of ECB and SWCB Infestation Generation by Planting Date, Given that Infestation Occurs

Planting Period	1st-Generation ECB	2nd-Generation ECB	1st-Generation SWCB	2nd-Generation SWCB
April 1–15	0.05	0.95	0.02	0.98
April 16–30	0.00	1.00	0.01	0.99
After April 30	0.00	1.00	0.00	1.00

B. Probability of Number of ECB or SWCB per Plant by Generation Given that Infestation Occurs (SWCB in parentheses)

ECB/Plant	SWCB/Plant	1st Generation	2nd Generation
1	0.1–0.2	0.90 (0.95)	0.70 (0.40)
2	0.3–0.4	0.10 (0.05)	0.20 (0.24)
3	0.5–0.6	—	0.10 (0.16)
	0.7–0.8	—	— (0.10)
	0.9–1.0	—	— (0.06)
	1.1+	—	— (0.04)

C. Probability of Type of Infestation in a Given Year

Type of Infestation	Probability
ECB and SWCB	0.25
ECB, SWCB, and spider mites	0.25
Spider mites only	0.25
None	0.25

Sources: Probabilities provided by Buschman; Sloderbeck; Higgins.

Empirical Results

The value of spraying non-Bt corn for European and southwestern corn borers in both irrigated and dryland corn was estimated. These estimations are important in calculating the value of Bt corn so that Bt corn can be compared to the most relevant alternative—non-Bt corn either with or without a corn borer spraying program.

The Value of a Spraying Program

Before estimating the value of Bt corn, it must be determined whether or not a spraying program targeting ECB and SWCB is profitable for farmers in southwest Kansas. Thus, the first step is to use the model to estimate the expected economic benefit of such a spraying program and compare that benefit to the cost of scouting fields for these insects to assess if, on average, it pays to have a spraying program. To estimate the expected spraying benefit, the model calculates the expected value of non-Bt corn with and without the spraying program. The difference in these values represents the maximum amount the farmer should be willing to pay for scouting. If actual scouting costs are greater than the expected benefit of the spraying program, then the farmer would not benefit from the program, on average.

The results show that spraying significantly controls pest damages. For each state of nature, or potential outcome, total pest-related yield loss, as a proportion of potential yield, is a multiplicative function of the individual infestations which may occur throughout the model's timeline. For example, suppose corn planted between May 1 and May 15 realizes later season (second-generation) infestation of one ECB per plant, 0.15 SWCB per plant, and spider mites. Using the estimated yield-loss information from tables 4 and 5, and assuming average mite damage of 5%, the base case yield percentage can be calculated as (1 - 0.0415) × (1 - 0.0434) × (1 - 0.05) = 0.871. Thus, total yield damage is nearly 13%. When a spray program is used, the yield losses for ECB, SWCB, and spider mites would be decreased to 0.83%, 0.65%, and 0.10%, respectively, with a total yield loss of 2.46%.

When analyzed across all possible states of nature, the spraying program results in a lower mean and standard deviation of pest damage levels compared to a non-spraying program. The mean yield loss without a spray program is 14.26%, compared to a mean of just 0.96% with a spray program. The standard deviation of yield losses without a spray program is 13.53%, whereas with a spray program, the variability is 8.96%. It should be noted that these results are based on point estimates for the input distributions, rather than Monte Carlo simulation. Input distributions were not simulated because there is strong evidence that spraying pays in southwest Kansas.

Results suggest a spraying program would be profitable for farmers expecting per acre revenues exceeding $167 (e.g., 83.5 bushels per acre at $2 per bushel, or 66.8 bushels at $2.50 per bushel). Therefore, all farmers using irrigation should profit, on average, from a spraying program targeting ECB and SWCB. However, this finding further implies that most farmers growing corn on dryland should also consider scouting and spraying fields for these insect pests. Average yields in this region of Kansas were 145.4 and 136.8 bushels per acre for irrigated and dryland, respectively, over the period 1982–2000 (USDA/NASS). At an expected revenue of $167 per acre, the expected benefit of spraying is just slightly greater than the scouting cost of $1.50 per acre. At an expected per acre revenue of $200, the expected benefit of spraying is $4.34 per acre, well above the scouting cost. Thus, nearly all farmers in this region should benefit from a program to spray for these insect pests. This result contrasts with the findings of Hyde et al. (1999) who concluded most Indiana farmers would not benefit from a spraying program.

The Value of Bt Corn

The previous results show the value of Bt corn should be based on a comparison with non-Bt corn under a spraying program. Thus, each of the simulations analyzed uses this as the benchmark for estimating the value of Bt corn. In total, 28 simulations were performed, each having 2,000 iterations, or random draws from the distributions for yield and price, yield losses, and insecticide efficacy. However, only seven basic analyses (denoted scenarios 1a–7a) based on different assumptions regarding the yield and price distributions, spraying costs, and infestation probabilities were performed, with the remainder being relatively minor alterations of this set (table 7).

From the distribution statistics reported in table 8, it is apparent that the average Bt values in scenarios 1a–4a and 7a are much higher than scenarios 5a and 6a. Note, scenarios 5a–7a reflect zero probability of more than one European corn borer or more than 0.2 southwestern corn borer per plant. However, scenario 7a places a greater

Table 7. Description of Simulated Scenarios

Scenario[a]	Yield Distribution	Price Distribution	Spraying Costs[b]	Infestation Probabilities[c]
1a	*TD*(109.98, 159.23, 166.99)	*TD*(1.68, 2.17, 3.29)	1	A
2a	*TD*(91.99, 153.17, 165.36)	*TD*(1.68, 2.17, 3.29)	1	A
3a	91.99	*TD*(1.68, 2.17, 3.29)	1	A
4a	91.99	1.68	1	A
5a	91.99	1.68	1/2	A
6a	91.99	1.68	1	B
7a	91.99	1.68	1	C

Note: *TD* denotes triangular distribution.

[a] The basic scenarios, designated with an "a," are specified as triangular distributions and simulate a risk-neutral decision maker. Scenarios designated with a "b" (see table 9) are the same as "a" scenarios, except are specified as uniform distributions.

[b] Spraying costs denoted by a "1" are costs as given in table 2. Costs designated as "1/2" are half of those reported in table 2.

[c] Probabilities designated as "A" are as given in table 6. The "B" probabilities are as given in table 6, except the probability of one ECB or 0.1 to 0.2 SWCB per plant given that infestation occurs = 1, and probabilities of type of infestation are 0.5 for "ECB and SWCB" and 0.5 for "none." The "C" probabilities are as given for "B," except probabilities of type of infestation are 0.75 for "ECB and SWCB" and 0.25 for "none."

Table 8. Distribution Statistics for Simulated Bt Values: Scenarios 1a–7a ($/acre)

Scenario	Minimum	Maximum	Mean	Std. Deviation
1a	22.81	50.82	34.60	4.88
2a	21.07	53.31	33.23	5.15
3a	18.56	34.67	24.97	2.72
4a	17.34	23.06	19.63	0.91
5a	9.47	16.52	12.52	1.07
6a	10.28	16.89	13.59	0.97
7a	15.94	24.35	20.08	1.45

Note: These scenarios are based on triangular distributions for the uncertain points.

probability on ECB and SWCB infestation than does scenario 6a. Results also show, on average, the value of Bt corn on dryland is less than $2 below the average value in irrigated corn, i.e., $34.60 versus $33.23.

In aggregate, the findings reveal, even in the least valued case (scenario 5a), the estimated distributions for Bt values were no less than $9.47 per acre. The means of the distributions were each well over $12 per acre. Simulation results of the seven scenarios indicate most farmers in southwest Kansas, whether raising corn under irrigated or dryland conditions, would benefit from planting Bt corn when the technology fee is less than $12 per acre. Furthermore, all would benefit with a technology fee less than $9.47 per acre, even in the least valued years.

It is apparent from these results that nearly all of the variability in Bt values is due to yield and price variability (table 8). The standard deviation of Bt values drops significantly when yield variability is removed (moving from scenario 2a to 3a), and falls sharply when price variability is removed (scenario 3a to 4a). The remainder of the variability in Bt values is due to variable insect damage and spraying control.

Table 9. Distribution Statistics for Simulated Bt Values: Scenarios 1b–7b ($/acre)

Scenario	Minimum	Maximum	Mean	Std. Deviation
1b	18.88	61.61	34.27	7.98
2b	17.83	60.30	33.19	7.75
3b	14.73	37.58	24.84	4.53
4b	15.29	23.88	19.50	1.44
5b	8.69	16.95	12.49	1.40
6b	9.06	17.47	13.48	1.52
7b	13.60	25.99	19.99	2.24

Note: These scenarios are based on uniform distributions for the uncertain parameters.

The effect of increasing the variability in the input distributions by specifying uniform, rather than triangular, distributions (denoted scenarios 1b–7b) is minor (table 9). Variability in the distribution of Bt values increases for all scenarios, but the means were little affected. This finding is as expected, given the means of the input distributions were held constant. Based on the results reported in table 9, nearly all farmers would benefit from planting Bt corn when the technology fee is less than $8.69 per acre, even in the least valued instances. On average, the typical producer would benefit when the technology fee is less than $12.49 per acre.

Because Bt corn is shown to be highly valuable to risk-neutral producers, results from analysis incorporating risk aversion are not displayed. When simulated under the assumption of strong risk aversion, however, the distributions of Bt values are shifted to the right. In all cases, the means and standard deviations are greater than in the risk-neutral case when risk aversion was increased. Risk-averse producers should be willing to pay at least $9.36 per acre for the Bt seed, compared to $8.69 in scenario 5b, and likely closer to $14 or more, depending upon assumptions used.

Conclusion

This analysis provides estimates of the value of Bt corn to farmers in southwest Kansas. Farmers in this region face much greater insect pressure than other U.S. Corn Belt farmers. While most of the Corn Belt is concerned only with European corn borer infestations, farmers in southwest Kansas face southwestern corn borer and spider mite pressure, in addition to the European corn borer. Building on the earlier work of Hyde et al. (1999), this research represents a significant improvement in estimating Bt values. The use of systematic sensitivity analysis allowed a distribution of Bt values to be estimated, rather than a point estimate. Thus, these results reveal how robust the value estimates are for the Bt trait in corn.

Simulation results suggest nearly all farmers in southwest Kansas would benefit from planting Bt varieties to control the array of insects prevalent in the region. This is true for farmers using irrigation as well as those growing dryland corn. In general, the value of Bt corn exceeds the per acre technology fee in much of southwest Kansas, which is around $14 per unit, or $5.25 per acre at a seeding rate of 30,000 seeds per acre (Buschman; Sloderbeck). Given that infestations of European corn borer (ECB), southwestern corn borer (SWCB), corn rootworm (CRW), and spider mites occur frequently in the region, and economic considerations may drive many farmers to adopt Bt corn, the future possibility of insects developing resistance to Bt is a concern. Thus, those farmers who adopt Bt corn must plant a 20% non-Bt corn refuge in accordance with Environmental Protection Agency requirements. [For details on the economics of refuge configurations, see Hyde et al. (2000).]

Several factors may bias these results either upward or downward. First, it was assumed a single spray application was used for second-generation infestations of ECB and SWCB, as well as spider mites and potentially CRW. This assumption may bias results downward. Second, spraying non-Bt corn for CRW and spider mites when ECB and SWCB population numbers are below their respective spraying thresholds may decrease yield damages from ECB and SWCB, thus biasing results slightly upward. Third, estimates of mechanical damage for SWCB (based on Lynch) may be well below what is actually experienced. Both Buschman and Sloderbeck indicate higher levels of lodging with SWCB damage. Therefore, these results may significantly underestimate Bt corn values when SWCB populations are high. Due to lack of field data, these effects cannot be modeled.

Although this analysis focuses on southwest Kansas, the results may be directly applicable to other regions facing similar insect pressure. For instance, data from Colorado indicate conditions in portions of that state are quite similar to those in southwest Kansas. Also, there may be other regions (e.g., portions of Texas, Oklahoma, Missouri, and Illinois) where SWCB is a relatively common insect pest. Further research should focus on modeling these regions explicitly, rather than simply drawing inferences from southwest Kansas conditions. However, findings of this research, in addition to the earlier work of Hyde et al. (1999), show that farmers with higher expected revenues per acre and those who realize relatively frequent infestations by ECB, and possibly other insects, can benefit from planting Bt corn.

One shortcoming of this analysis is the exclusion of many sources of yield variation. Those sources considered common to both Bt and non-Bt corn were excluded. Weather is likely the most important source. Although weather effects are incorporated here as they affect planting date and probability of pest infestation, other weather effects are ignored. Consequently, the variability of yield levels is not as high in this study as some other analyses may report. Coble, Heifner, and Zuniga, for example, find yield coefficients of variation (CV) for dryland and irrigated corn of 20–40% and 15%, respectively. The greatest CV found here is 11.9% for non-Bt corn and 11.5% for Bt corn. (These are similar because spraying controls insect pests reasonably well.) All other CVs are less than 10%. Including other sources of yield variability would enhance the study, but was not undertaken here.

Finally, yield variability may actually increase the farmer's risk. A recent investigation by Hurley, Mitchell, and Rice, building upon the earlier work of Horowitz and Lichtenberg, shows that increased risk from planting Bt corn reduces its value by 10% to 25%. The value of Bt corn was decomposed into two components, the value of yield protection and the risk-management benefit. The risk-management benefit, shown to be negative, lowered the value of Bt corn. An interesting extension would be to apply the Hurley, Mitchell, and Rice methodology to the southwest Kansas region, where the analysis would account for the southwestern corn borer and spider mites.

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