Use of Transgenic *Bacillus thuringiensis* Berliner Corn Hybrids to Determine the Direct Economic Impact of the European Corn Borer (Lepidoptera: Crambidae) on Field Corn in Eastern Canada

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ABSTRACT Transgenic corn expressing *Bacillus thuringiensis* Berliner (*Bt* corn) (Maximizer and Yieldgard hybrids, Novartis Seeds), non-*Bt* isolines and high-performance (check) hybrids were evaluated for European corn borer, *Ostrinia nubilalis* (Hübner), damage and grain yield in commercial strip plots across Ontario in 1996 and 1997. *Bt* corn hybrids reduced stalk tunneling damage by 88–100%. In 1996, minimal damage was found in locations where only one generation of European corn borer occurred per year. *Bt* corn proved its greatest potential for reducing the number and length of cavities below the primary ear in locations where two generations of European corn borer were present. A yield response to using *Bt* hybrids only occurred when levels of tunneling damage exceeded 6 cm in length. European corn borer infestations resulted in a 6 and 2.4% reduction in yield for 1996 and 1997, respectively, when *Bt* hybrids were compared with their non-*Bt* isolines. A linear relationship was found between tunnel length per plant in centimeters (x) and yield protection (%) obtained from using *Bt* corn (y) ($y = 1.02 + 0.005x$, $r^2 = 0.7217$). At a premium of $34.58 Canadian (CDN) per hectare for *Bt* corn seed, an infestation of at least 6 cm of corn borer tunneling per plant was required to break even at a market price for corn of $2.50 per bushel CDN. During the period of study, low infestations (0–2 cm) of European corn borer occurred at 25% of the locations assessed, moderate infestations (4–6 cm) occurred at 42% of the locations, and high infestations (>6 cm) occurred at 33% of the locations. At a corn price of $3.00 per bushel CDN and seed premiums of $34.58 per hectare CDN, 5 cm of tunneling was required for a return on investment in *Bt* seed, comprising only 55% of the growers in the study. With infestations of more than 6 cm of tunneling occurring only 33% of the time, a return on seed investment would be realized in only one of three growing seasons. At a seed premium of $24.70 per hectare CDN per year, at least $74 per hectare CDN in the year of infestation would be required to make up for the two years of no return. In this study, a $74 per hectare CDN return at a corn price of $9.26 per hectare CDN with >16 cm of tunneling damage would have occurred only 7.3% of the time.

KEY WORDS European corn borer, *Ostrinia nubilalis, Bacillus thuringiensis, Bt* corn, field corn, economic impact

THE RELATIVE ECONOMIC importance of European corn borer, *Ostrinia nubilalis* (Hübner), in eastern Canada has been under dispute for some time (Chiang and Hudon 1973; D.G.R. McLeod, AAFC-SCPFRC, London, personal communication). Most have argued that the use of insecticides for controlling European corn borer has not been warranted in field corn.

Hybrid corn, genetically transformed to contain the gene responsible for Cry 1Ab protein synthesis, was registered and used commercially in Canada for the first time in 1996 to control European corn borer (CFIA 1996a, 1996b). Cry 1A proteins from the soil microorganism *Bacillus thuringiensis* variety *kurstaki* are specific toxins to some lepidopterans. Three *Bacillus thuringiensis* (*Bt*) corn events were initially registered for use in Canada. Event 176 constructed by Novartis Seeds (Arva, Ontario) expresses toxin only in green tissue, pollen, and stalk tissue (CFIA 1996a). Event *Bt*-11 by Novartis Seeds and MON810 by Monsanto Canada (Mississauga, Ontario) express the toxin in the pollen, tassel, silk, and kernels, as well as green tissue (CFIA 1996b, 1997). With the advent of *Bt* corn the ability to measure economic loss in corn caused by European corn borer damage has been much improved.

Before the advent of *Bt* corn, yield loss to European corn borer damage was difficult to quantify because

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chemical control was variable and it was effective generally only up to 80% (Mason et al. 1996). Only weak evidence regarding the effect of European corn borer damage on corn yield was available. However, with genetically altered plants ≈99% control of European corn borer can be obtained and the relationship between corn borer damage and yield loss can be defined more closely (Rice and Pilcher 1998).

Koziel et al. (1993) reported the first field results for event 176, in which effective control of European corn borer was achieved without pesticide applications. Conventional corn was damaged with severe leaf feeding and stalk tunneling, whereas those expressing *Bt* had very little damage. These results have been confirmed by other researchers (Jansens et al. 1997, Graeber et al. 1999, Lauer and Wedberg 1999, Clark et al. 2000). In all cases, *Bt* hybrids, regardless of the event, had less leaf feeding, stalk tunneling, and shank tunneling compared with their non-*Bt* counterparts. Few studies have determined the potential economic benefit that could be derived from this new technology relative to its cost to the producer and, more precisely, no such studies have been reported for eastern Canada. Graeber et al. 1999 found an increase of >10 bushels per acre from using *Bt* corn in Illinois, Iowa, and Indiana. However, Rice and Pilcher (1998) and Lauer and Wedberg (1999) detected that *Bt* corn only showed yield protection benefits in outbreak years in Iowa and Wisconsin, respectively. In years when corn borer populations were not endemic, non-*Bt* hybrids were able to perform as well or better than the *Bt* hybrids. Because the premium for *Bt* hybrid seed has ranged from $21.74 to $34.58 CDN per hectare (unpublished commercial data), a yield advantage in excess of the added cost is necessary for economic sustainability.

This study was undertaken to compare the cost effectiveness of growing *Bt* corn compared with non-*Bt* isolines and high-performance check hybrids of field corn under natural European corn borer infestations in eastern Canada, and to derive a relationship between corn borer pressure and yield loss.

Materials and Methods

Plot Layout. Plots consisting of strips of various hybrids, planted the length of the field, were located in 43 fields in Ontario in 1996 and 1997. All strips within each location had the same width, ranging from 4 to 12 rows. Locations were distributed among six crop heat unit (CHU) regions (Brown and Bootsma 1993): 2600, 2700, 2800, 2900, 3000, 3100+ in 1996, and within a seventh heat unit region (3200) in 1997. Plots were planted and maintained by commercial growers. Within each field, strips of three hybrids were monitored for European corn borer infestation throughout the season. Two of the strips consisted of a *Bt* hybrid (either event 176 or *Bt*-11 from Novartis Seed) and its non-*Bt* isoline. The third strip consisted of a high-performance check hybrid, selected from the Ontario Hybrid Corn Performance Trials (Ontario Corn Committee 1997, 1998) of the previous year on the basis of its agronomic adaptation to the region, its high yield potential and its ability to resist stalk lodging (Table 1). A common field-tester hybrid was also planted at all locations in three replicates across the field, to measure variability of infestation and edaphic factors at each location. Because each of the three hybrid types studied were not replicated within the field, the entire location was discarded from the study if yield varied by >24.7 bushels per hectare (10 bushels per acre) among the field-tester hybrid replicates at any location.

Table 1. Corn hybrids evaluated under natural European corn borer infestation in each crop heat unit region in 1996

Crop heat unit	Event	Hybrid		
		Bt	Isoline	Check
		1996		
2600	176	Max 40	G-4030	P3902
2700	176	Nax 40	G-4030	N2555
2800	176	Max 78	G-4120	P3860
2900	176	Max 96	G-4193	N3030
3000	176	Max 88	G-4273	P3723
3100+	176	Max 88	G-4273	P3515
		1997		
2600	Bt-11	N17-C5	N15-B4	4046
2700	Bt-11	N2555Bt	N2555	4064
2800	Bt-11	N3030Bt	N3030	P3860
2900	176	Max 86	G-4187	P3752
3000	176	N47-H7	G-4286	P3752
3100	176	N47-H7	G-4286	DK493
3200	176	N47-H7	G-4286	P3515

Damage Assessment. Four sampling sites consisting of 10 consecutive plants were set up equidistantly apart (at least 15 m) in the middle two rows of the *Bt*, isoline, and check hybrid strips. The first and last (fourth) sites were at least 12 m from the field margin to avoid any edge effects. No insecticides were used in these plots. Just before harvest, 10 consecutive plants from each sampling site were dissected lengthwise through the stalk, from the tassel to the ground. The total number and length of feeding cavities were recorded. The plots were harvested between mid-October and the end of November with commercial harvesting equipment, and plot yields were weighed using electronic weigh wagons. Yields were corrected to 15.5% moisture.

Data Analysis. For each field location, means of subsample data from each hybrid strip were calculated for tunneling damage and yield differences proportional to the isoline. Data were grouped by location according to their CHU potential. The data were analyzed as a randomized complete block with N replications (where N = number of sites within a CHU area) using unbalanced analysis of variance (ANOVA) via SAS PROC GLM (SAS Institute 1994). Means were separated using Tukey's studentized range honestly significant difference (HSD) test to determine significant differences between mean damage values for transgenic hybrids versus isolines and checks, at a 95% confidence level. Because tunneling measurements violated the assumption of normality, they were transformed to $(x + 0.5)$ before ANOVA.

Yields are reported in bushels/acre and prices in $Canadian/hectare to reflect an effort to construct a model conversant with North American corn producers.

Relationship Between Tunneling Damage and Yield Protection. The difference between average tunnel length per plant of *Bt* hybrids and their non-*Bt* isolines was calculated at each location throughout Ontario. Yield protection was calculated as a ratio of the yield (bu/ha) of the *Bt* hybrids over the yield of the isoline hybrids from these plots. The relationship between the difference in tunneling damage per plant found in *Bt* and isoline hybrids and yield protected by using *Bt* technology was tested using a simple linear regression (SAS Institute 1994) in the form:

$$Y = B_0 + B_1X_1, \quad [1]$$

where Y = yield protection as a ratio (*Bt*/Isoline yield) and X_1 = average tunnel length (cm) per plant.

Return on Investment. Using equation 1, expected yield protection was calculated for a range of levels of infestation indicated by mean tunnel length per plant. Return on investment could then be determined using the following equation:

$$R = [Y * M * C] - P, \quad [2]$$

where R = return on investment using *Bt* protection ($/hectare), Y = yield protection using *Bt* protection at a certain level of infestation and expected yield (bu/ha), M = estimated current market value of corn ranging from $2.50 to $3.75/bu (Ontario Corn Producers' Association 1998), C = expected level of control using *Bt* corn @ 0.96 (Ostlie et al. 1997), and P = additional cost of purchasing *Bt* seed over non-*Bt* seed (from $21.74 to $34.58/ha).

The model was tested by setting expected yield at 296 bushels per hectare (120 bushels per acre), according to the average yield in Ontario over the previous 5 yr (Ontario Corn Producers' Association 1998). *Bt* hybrids and non-*Bt* isolines were assumed to have the same hybrid characteristics, with the exception of the *Bt* construct. Both *Bt* events (event 176 and *Bt*-11) were assumed to control European corn borer equally at an average of 96% (Ostlie et al. 1997).

To determine the return on investment at varying farm gate prices, calculations were made using a set seed premium of $34.58 per hectare. This was the highest premium for *Bt* seed in the year following introduction (Ontario Corn Producers' Association 1998), representing the worst case scenario. Conversely, calculations were also made by using a set farm gate price of $2.50 per bushel and by varying the seed premium, to show a worst case scenario when the lowest price for corn was received.

Sensitivity Analysis. To test the sensitivity of return on investment in equation 2, each variable was given a range of values within realistic upper and lower limits (Table 2), while all other parameters were held constant. All linear relationships were normalized to the same scale and plotted. Slopes for the relationships of each parameter against return on investment were evaluated and compared visually.

Table 2. Range of values used to test the sensitivity of each parameter in the equation R = [Y * M * C] − P

Parameter	Constant	Lower limit	Upper limit
Expected yield	296 bu/ha	247 bu/ha	494 bu/ha
Market value of corn (M)	$3.00/bu	$2.50/bu	$3.75/bu
Expected control (C)	0.96	0.75	1
Seed premium of *Bt* (P)	$24.70/ha	$14.82/ha	$39.52/ha
Yield protection (Y)	17.78 bu/ha	−6.18 bu/ha	39.52 bu/ha

Results

Tunneling Damage. The greatest amount and length of tunneling occurred in the higher CHU rating regions where the bivoltine strain was present in 1996 (Fig. 1). In 1997, greater damage was noted in locations within the lower CHU regions, whereas in the bivoltine regions, little damage occurred (Fig. 1). Overall, *Bt* corn hybrids had significantly lower European corn borer damage than isoline or check hybrids. *Bt* corn hybrids additionally reduced the amount of damage observed below the primary ear in all corn growing regions. Stalk breakage ratings did not differ among hybrids in either 1996 or 1997.

Yield. Hybrid strips were not replicated at each location, therefore yield could not be statistically analyzed within fields. Instead, data were blocked according to crop heat unit rating for analysis. Only 27 of the 50 locations in 1996 met the criterion of having <10% variation among the three replicated field-tester hybrid strips, and only these were included in the study. There were no differences in yield within each crop heat unit rating among the three hybrid types with the exception of those in the 3000 and 3100+ CHU regions (Fig. 2). In these regions, yields of *Bt* and check hybrids were similar and generally higher than the yields of the isoline.

In 1997, only 28 out of the 51 locations had <10% variation in the field-tester hybrid strips and only these were harvested. Weather conditions were cooler than normal with ≈150 less CHU accumulated during the season. The hybrids did not reach their full yield potential. As a result, there were no differences in yield among the three hybrid types, with the exception of a *Bt* hybrid that had greater yield than the check hybrid in 2600 CHU fields and the check hybrid in 3200 CHU fields that yielded greater than the *Bt* and isoline hybrids (Fig. 2).

For relating yield response to European corn borer pressure, yield data from all plots were grouped by year with respect to three levels of infestation. Infestation levels for each location were assigned on the basis of tunnel length below the ear for the susceptible isoline, low infestation = 0–2 cm, moderate = 2–6 cm, and high = 6–12 cm of tunneling (Table 3). Yields were calculated as proportions of the corresponding non-*Bt* isoline (=100), assuming that damage to the non-*Bt* isoline represents the expected degree of infestation and yield loss. Any proportionate yield above this level would represent the amount protected by a *Bt* hybrid or a resistant or tolerant variety like the high-performance check. In 1996, there was no dif-

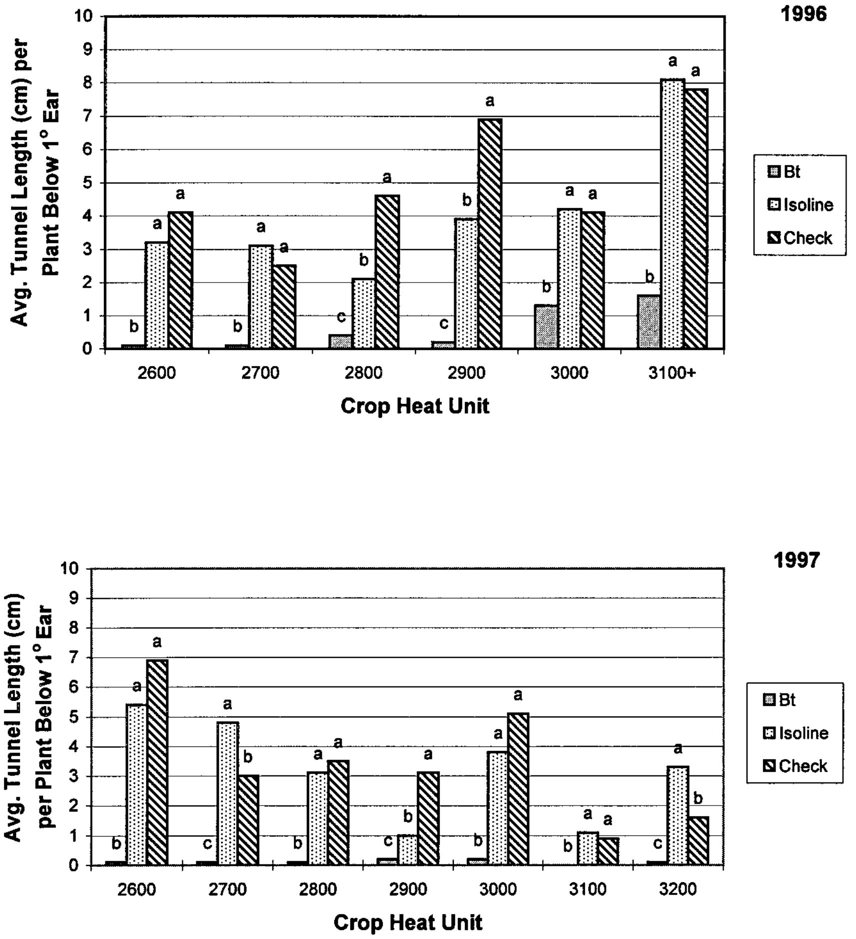


Fig. 1. Average length of tunneling below the primary ear by European corn borer larvae during late season damage assessment in *Bt*, non-*Bt* isoline, and high-performance check hybrids grown in each crop heat unit region in Ontario in 1996 and in 1997. Means within each crop heat unit region followed by the same letter are not significantly different ($P > 0.05$; Tukey's HSD) after ($\sqrt{x} + 0.5$) transformation.

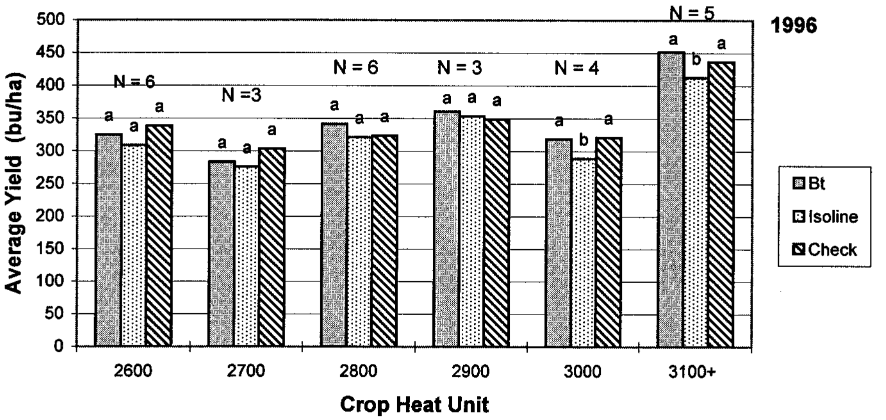
ference in yield between isoline and *Bt* or between *Bt* and check hybrids in low and moderate infestations. Under high infestations, both *Bt* and check hybrids had greater yields than the isoline. Although not significant under high infestations in 1997, *Bt* hybrids had numerically higher yields than non-*Bt* isoline.

Relationship Between Tunneling Damage and Yield Protection. A linear relationship was obtained between differences in tunneling damage per plant among *Bt* and isoline hybrids (x), and yield protection (y), ($P = 0.009$, $F = 7.343$ and $r^2 = 0.7217$) (Fig. 3). Yield protection (y) was defined as the proportion of *Bt* hybrid yield to non-*Bt* isoline yield in the relationship:

$$Y = 1.02 + 0.005X. \quad [3]$$

Expected Yield Versus Damage at Harvest. Using equation 3, potential yield protected by using *Bt* corn was calculated at various levels of expected yield (Table 4). For example, if a grower usually averages 296 bushels per hectare (120 bushels per acre) and upon inspection finds an average of 6 cm of tunneling damage in a non-*Bt* hybrid he/she has grown, a yield loss of 14.8 bushels per hectare could be expected. Therefore, a 14.8 bushels per hectare yield advantage by using a comparable *Bt* hybrid would result.

Return on Investment at a Set Premium. Using equations 2 and 3 the return on investment ($CDN per hectare) due to the use of *Bt* corn was calculated at a fixed seed premium of $34.58 per hectare while varying damage and corn price (Fig. 4). To recover the cost of the seed premium of $34.58 per hectare, infestations must be high (>6 cm of tunnel/plant) and corn prices at least $2.50 per bushel. If corn prices are as high as $3.50, the use of *Bt* corn will be profitable at moderate levels of damage (3 cm per plant). To achieve a return on investment of $24.70 per hectare above the $34.58 premium, potential damage levels must be as high as 14 cm of tunneling per plant.



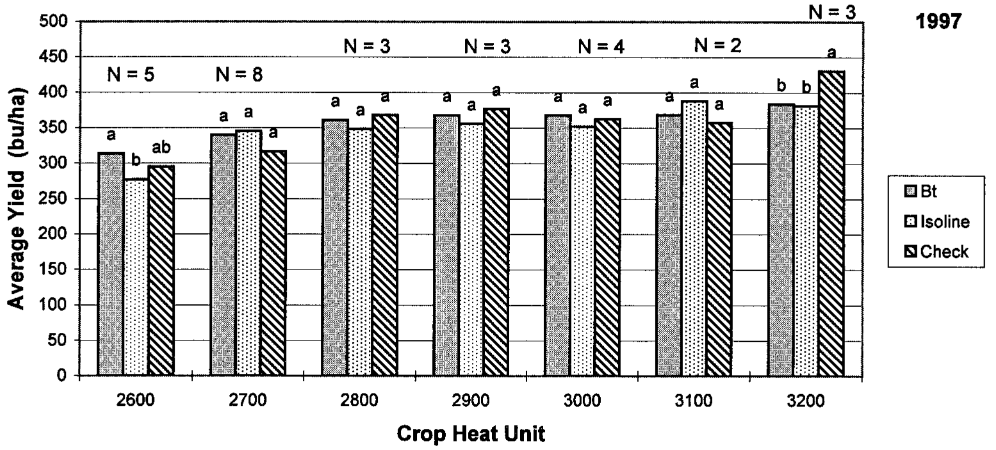


Fig. 2. Average yield among *Bt*, non-*Bt* isoline, and high-performance check hybrids grown under natural infestation of European corn borer, within each crop heat unit region in Ontario in 1996 and in 1997. Means within each crop heat unit region followed by the same letter are not significantly different ($P > 0.05$; Tukey's HSD) after ($\sqrt{x} + 0.5$) transformation.

Return on Investment at a Set Corn Price. Return on investment was calculated with the corn price fixed at $2.50 per bushel while varying damage and corn seed premiums (Fig. 5). To achieve a return of $1 per hectare on investment using *Bt* seed with a $21.74 per hectare premium, at least 3 cm of tunneling per plant

Table 3. Yield as a proportion of isoline for *Bt*, non-*Bt* isoline and check hybrids in low, moderate and high infestations of European corn borer in Ontario in 1996 and 1997

Infestation level	Hybrid type	1996			1997		
		No. of fields (*N*)	Yield range (bu/ha)	Yield as a proportion of isoline (=100)	No. of fields (*N*)	Yield range (bu/ha)	Yield as a proportion of isoline (=100)
Low (0–2 cm)	*Bt*	10	212–464	104ab	12	287–442	101a
	Isoline	10	109–440	100b	12	259–400	100a
	Check	10	227–430	107a	12	257–427	101a
Moderate (2–6 cm)	*Bt*	8	217–361	105a	9	299–410	105a
	Isoline	8	222–346	100a	9	282–378	100a
	Check	8	274–366	100a	9	274–442	104a
High (6–12 cm)	*Bt*	9	245–469	108a	9	292–375	107a
	Isoline	9	227–425	100b	9	282–373	100a
	Check	9	237–482	106a	9	232–348	100a

Means within each infestation level followed by the same letter are not significantly different ($P > 0.05$; Tukey's HSD).

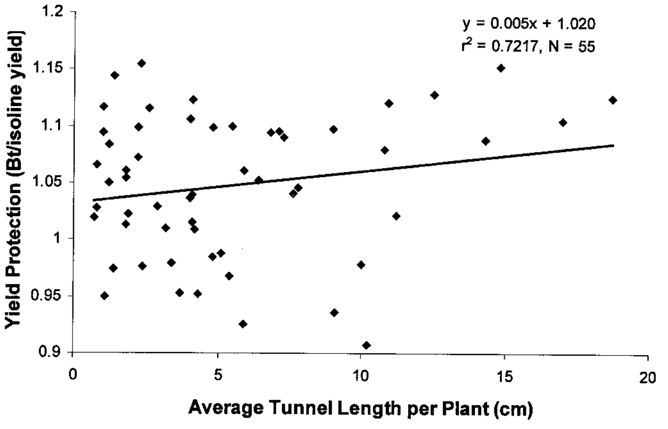


Fig. 3. Simple linear regression of average tunnel length per plant and yield protection (proportion of *Bt* hybrid yield over non-*Bt* isoline yield) from all locations in Ontario under natural infestation of European corn borer in 1996 and 1997 ($P = 0.0091$).

was required. If the seed premium was $34.58 per hectare, at least 6 cm of tunneling per plant was required to break even.

The frequency of occurrence of low, moderate and high European corn borer infestations as determined by tunnel length in Ontario in 1996 and 1997 was calculated (Table 5). Low infestations (0–2 cm) occurred most frequently at 25.5% of the 55 locations, while high infestations (>6 cm) occurred at an average of 33% of the locations. The model shows that at high seed premiums and low corn prices, an expected infestation of at least 6 cm of tunneling would be required to break even using *Bt* corn. From results of strip plot data in 1996 and 1997, if those growers received $3.00 per bushel for their corn, and paid $34.58 per hectare for *Bt* seed, only 55% would have recovered their investment in *Bt* corn seed premiums. These growers that broke even were located in the 2800, 2900, and 3100+ CHU regions in 1996 and in the 2600, 2700, and 3000 CHU regions in 1997. The model was most sensitive to Y (yield protection using *Bt* seed). Seed premium (P) and corn price (M) followed at second and third most sensitive. Expected yield had the least impact on return on investment.

Table 4. Potential yield protection obtained using *Bt* hybrids in bushels per hectare in Ontario under various levels of expected corn yields and lengths of tunneling damage caused by European corn borer larvae

Tunnel length (cm)	Yield protection (bu/ha)				
Expected yield (bu/ha)	247	296	346	395	445
2	7.4	8.9	10.4	11.9	13.3
4	9.9	11.9	13.8	15.8	17.8
6	12.4	14.8	17.3	19.8	22.2
8	14.8	17.8	20.7	23.7	26.7
10	17.3	20.8	24.2	27.7	31.1
12	19.8	23.7	27.6	31.6	35.6

Discussion

Bacillus thuringiensis corn reduced stalk tunneling damage caused by European corn borer larvae by as much as 88–100%. Other trials carried out in the north central Corn Belt had similar results (Jansens et al. 1997, Graeber et al. 1999, Lauer and Wedberg 1999, Clark et al. 2000). In Ontario, under low infestations, there was no difference in yield of *Bt* corn compared with yields of isoline and high-performance check hybrids. In contrast, Graeber et al. 1999 found an 11 bu/ac yield advantage when using *Bt* corn compared with non-*Bt* hybrids even under low infestations but indicate more of an advantage to using *Bt* hybrids when infestations are higher. In Ontario, under high infestations of European corn borer, *Bt* corn hybrids

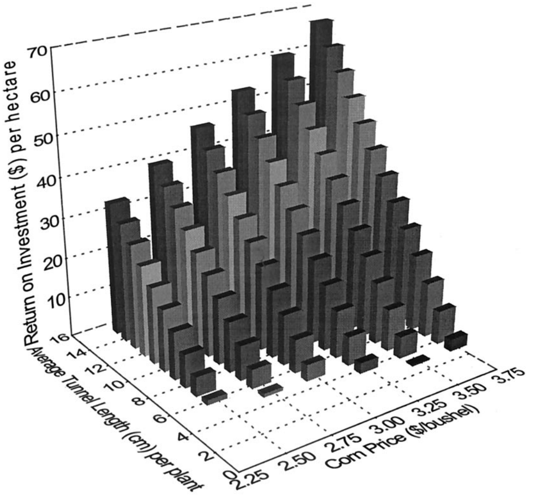


Fig. 4. Return on investment using *Bt* corn at a set seed premium of $34.58 per hectare, with various average tunnel lengths per plant and corn prices. Expected yield was set at 296 bushels per hectare (120 bushels per acre).

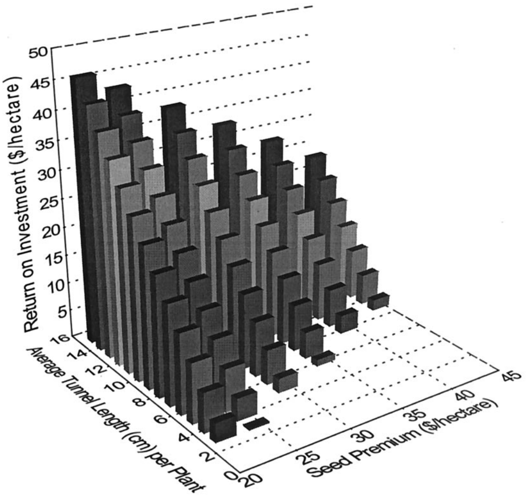


Fig. 5. Return on investment using *Bt* corn at a corn price of $2.50 per bushel, with various average tunnel lengths per plant and corn seed premiums. Expected yield was set at 296 bushels per hectare (120 bushels per acre).

produced comparable yields to the high-performance check hybrids and both of these exceeded that of non-*Bt* isolines. These data suggest that if an outbreak could be predicted or fields were located in areas with consistently heavy infestations, a *Bt* hybrid could be used as insurance against yield loss. Our data do not support the notion that *Bt* hybrids in general are higher yielding than conventional hybrids. On the contrary, *Bt* crop protection must be incorporated with elite corn genetics to maximize yield when European corn borer is absent. Similar results were found by Rice and Pilcher (1998) and Lauer and Wedberg (1999) where some non-*Bt* hybrids yielded as well or better than the *Bt* hybrids unless in outbreak years.

When *Bt* hybrids were compared with their non-*Bt* isolines, tunneling by European corn borer below the primary ear averaged 4.5 and 3.4 cm in the non-*Bt* hybrids in 1996 and 1997, respectively. Also, European corn borer caused a 6 and 2.4% decrease in yield of isolines compared with the *Bt* hybrids in 1996 and 1997, respectively. This average of 5% yield reduction would have resulted in a $37 per hectare loss as opposed to the $21.74 to $34.58 per hectare cost of purchasing *Bt* seed. With such losses, European corn borer could be considered an economic pest in Ontario. However, only 55% of our grower cooperators using *Bt* hybrids broke even using this technology if they had to pay the higher seed premiums of $34.58 per hectare and received $3.00 per bushel for their crop in 1996 and 1997.

European corn borer populations fluctuate from year to year. If 6 cm of tunneling occurs 33% of the time, a return on *Bt* seed investment might be expected one in three growing seasons. Assuming a seed premium of $24.70 per hectare per year, a return of over $74 per hectare must be realized in one of the three years to make up for the other two years. Our data suggest a return on investment of $74 per hectare would only occur when corn is priced at $3.75 per bushel and there is 16 cm of tunneling damage. However, only 7.3% of the growers from this study received >12 cm of tunneling damage in 1996 and 1997.

As transgenic *Bt* corn acreage increases, populations of European corn borer should decline in succeeding years, reducing the expectation of high infestations. As the frequency of high infestations decreases, so does the opportunity for a return on investment given a fixed seed premium and a stable value for grain corn. The sporadic nature of European corn borer populations, and the relatively low frequency of return will limit the adoption of this technology, especially when commodity prices are low.

Several assumptions were made in testing this model. Expected yield was set at the 5-year average of 296 bushel per hectare (120 bushel per acre) and all *Bt* hybrids were assumed to be equal in their degree of control. Other studies have found a difference in control between event 176 and *Bt*-11 hybrids. Event 176 hybrids were found to average 96% and 75% control for first- and second-generation larvae, respectively; whereas *Bt*-11 hybrids averaged 96% control throughout the season (Ostlie et al. 1997). In our study, nine locations (20%) in 1996 (in the 3000 and 3100+CHU regions), which were under high infestations (>6 cm of tunneling), were planted with hybrids containing event 176. An average of 88% control was recorded preharvest. The remaining 36 locations (80%) in both years resulted in 99% control. Therefore, assuming control to 96% was realistic. Also, data used to generate the model were based on the performance of *Bt* hybrids from one seed company source and may not apply to other *Bt* hybrids.

Growers located in regions where European corn borer populations are consistently high each year would be more likely to profit from using *Bt* hybrids than growers in regions where European corn borer damage is generally low. These results concur with Hyde et al. 1999, who found there to be much more of an advantage to growers who have a 40% or greater probability of an European corn borer infestation. Fields in regions with two or more generations of

Table 5. Frequency of occurrence of low, moderate, and high infestations of European corn borer larvae in Ontario according to length of tunneling per plant across Ontario in 1996 and 1997

	Infestation rating						
	Low		Moderate		High		
Tunneling (cm)	0.0–2.0	2.1–4.0	4.1–6.0	6.1–8.0	8.1–10.0	10.1–12.0	<12.0
Frequency (%)	25.5	20.0	21.8	10.9	5.5	9.0	7.3

European corn borer per year are more likely to be under constant European corn borer pressure, and growers might want the assurance of full-season damage protection with *Bacillus thuringiensis.*

Market prices (driven also by consumer acceptance of genetically modified crops) will also play a role in determining whether a grower will invest in *Bt* technology. The sensitivity plots suggested that both seed premium and corn price had a large impact on return on investment. Returns to higher premiums were less affected at higher corn prices.

Another risk associated with adopting the *Bt* technology is the potential for the development of pest resistance. A resistance management strategy employing a refuge planting of 20% non-*Bt* corn within 400 m of all *Bt* corn has been deployed to delay the development of resistance (Ostlie et al. 1997, Onstad and Guse 1999, Tenuta et al. 1999). Using this strategy also incurs a cost to the producer in labor, seed inputs and potential losses due to European corn borer damage in the nonprotected strips.

Bacillus thuringiensis corn should not be and probably will not be planted as a matter of course. Corn producers have a long history in calculating the costs associated with new technology, where risks and benefits are carefully weighed. *Bt* corn is, however, a valuable tool against European corn borer when the infestation and economies justify its use.

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