ELSEVIER

Crop Protection 21 (2002) 157–169

Crop Protection

www.elsevier.com/locate/cropro

Efficacy and risk efficiency of sweet corn hybrids expressing a *Bacillus thuringiensis* toxin for Lepidopteran pest management in the Midwestern US

Eric C. Burkness[a], W.D. Hutchison[a,*], R.A. Weinzierl[b], J.L. Wedberg[c], S.J. Wold, J.T. Shaw[d]

[a] *Department of Entomology, University of Minnesota, 219 Hodson Hall, 1980 Folwell Ave., St. Paul, MN 55108-6125, USA*
[b] *Crop Sciences-Entomology, University of Illinois, S-522 Turner Hall, 1102 South Goodwin Ave., Urbana, IL 61801, USA*
[c] *Department of Entomology, University of Wisconsin, 237 Russell Labs, Madison, WI 53706, USA*
[d] *Center for Economic Entomology, Illinois Natural History Survey, 607 E. Peabody Dr., Champaign, IL 61820, USA*

Received 26 January 2001; received in revised form 25 May 2001; accepted 4 June 2001

Abstract

Field studies were done in 1997 and 1998 to assess the efficacy of sweet corn hybrids expressing the *Bacillus thuringiensis* (Bt) toxin, Cry 1Ab, for control of *Ostrinia nubilalis* (Hübner), *Helicoverpa zea* (Boddie), and *Spodoptera frugiperda* (J.E. Smith). Trials were performed over multiple planting dates and locations in Illinois, Minnesota, and Wisconsin, USA. The Bt hybrids tested are based on the BT-11 event (Novartis Seeds, Inc.) and express the Bt toxin in green and reproductive tissues. In both years, except when pest densities were low, Bt hybrids provided significant reductions in larval densities for each pest species, often 100% control for *O. nubilalis*, when compared to non-Bt isolines. This resulted in significant increases in percent marketable ears, which ranged from 70–100% and 90–100% marketability for fresh-market sale and processing, respectively. Expected utility analysis, based on all data sets, was conducted by multiplying each marketability outcome by its frequency of occurrence and averaged for each produce type, either fresh-market or processing. Expected utility results indicated that the Bt hybrids provided 75–99% and 94–99% marketable ears for fresh-market and processing, respectively. By contrast, the non-Bt hybrids provided only 14–34% and 41–56% expected marketable ears for fresh-market and processing, respectively. Moreover, variability (risk) in marketability, when compared with the non-Bt isolines, was lower for the Bt hybrids. Coefficients of variation (CV), for all three states combined, averaged 1.17 and 0.84 for non-Bt fresh-market and processing, respectively; however, CVs for Bt fresh-market and processing were only 0.17 and 0.05, respectively. These results suggest that Bt hybrids can provide consistent performance, regardless of the pest complex, pest density, or geographic location in the Midwestern US. Additional analyses, including comparisons with insecticide control, and the costs associated with the use of insecticides versus Bt sweet corn, are necessary to assess the full benefit of using Bt sweet corn.

Keywords: Transgenic sweet corn; Expected utility; *Ostrinia nubilalis*; *Helicoverpa zea*; *Spodoptera frugiperda*

In the upper Midwestern US, control of lepidopteran pests including the European corn borer, *Ostrinia nubilalis* (Hübner), corn earworm, *Helicoverpa zea* (Boddie), and fall armyworm, *Spodoptera frugiperda* (J.E. Smith), in sweet corn, *Zea mays* L., is of primary concern for commercial growers. With conventional insecticides, this task often is difficult because of variable arrival time of pest populations, pest behavior, timing of insecticide applications, and effectiveness of insecticide treatments (Bartels and Hutchison 1995, Flood et al., 1995, Rinkleff et al., 1995). Recently, with the advent of transgenic sweet corn engineered to express *Bacillus thuringiensis* (Berliner) (Bt) toxins, many of the challenges of lepidopteran pest control have been met. Presence of the Cry Bt gene in transgenic Bt sweet corn allows for the production of Bt toxins in green and reproductive tissues of the sweet corn plant. The first sweet corn hybrids to express Bt were developed by Novartis Seeds, Inc. (Nampa, ID) using the 35S promoter (Armstrong et al., 1995), and the gene for Cry1Ab Bt protein (Lynch et al., 1999a). This event,

*Corresponding author.Tel.: +-612-624-1767; fax: +1-612-625-5299.

E-mail address: hutch002@tc.umn.edu (W.D. Hutchison).

0261-2194/02/$ - see front matter
PII: S0261-2194(01)00080-1

referred to as BT-11, provides high Bt expression in field corn (Ostlie et al., 1997), and has also been shown to provide high Bt concentrations in green leaf, silk, and kernel tissue of several sweet corn hybrids (Lynch et al., 1999a). In addition to providing high levels of control against *O. nubilalis* (Burkness et al., 2001), Novartis' Bt sweet corn hybrids have been shown to provide high levels of control against *H. zea* and *S. frugiperda* (Lynch et al., 1999a).

Recent studies (Lynch et al., 1999a, Lynch et al., 1999b, Burkness et al., 2001) have indicated that use of Bt sweet corn hybrids may result in eliminating or greatly reducing insecticide applications for lepidopteran pests in southern and midwestern corn producing regions of the United States. In addition to high levels of pest control, the use of Bt sweet corn has provided high levels of marketable ears for both fresh-market and processing sweet corn production (Burkness et al. 2001).

Although the efficacy of Bt sweet corn for *O. nubilalis* control was recently evaluated in Minnesota (Burkness et al., 2001), the technology has not been tested over multiple planting dates or in all major sweet corn production areas of the Midwestern US. Typically, the performance of new pest control technologies is limited to percent control or marketability at one or a few locations in a limited geographic area. However, even with multiple data sets, little consideration has been given to what the probability (risk) of pest control may be under different production scenarios (i.e., environmental variation year to year, pest complex composition, and geographic location). Expected utility analysis (e.g., Carlson, 1970; Moffitt et al., 1983) allows for multiple data sets and environmental conditions to be incorporated into a more thorough assessment of the performance of various pest control strategies. By determining the frequency of an insect control outcome, which occurs with a given pest control strategy (i.e., payoff), the probability of each insect control outcome may be calculated. In addition, the variation in expected utility (e.g., standard deviation) provides an estimate of the risk associated with the pest control strategy (Carlson, 1970). Through this analysis a producer can choose a desired level of marketable produce and determine the level of probability (risk) that is associated with achieving that goal.

The purpose of this paper is to document the efficacy of several BT-11 sweet corn hybrids, expressing Cry1Ab toxin, in Illinois, Minnesota, and Wisconsin, USA by comparing them with conventionally bred susceptible hybrids for control of *O. nubilalis*, *H. zea*, and *S. frugiperda* and their associated plant damage. Furthermore, via the use of expected utility analysis, we estimate the benefit and variability in pest control, by Bt vs. susceptible sweet corn hybrids for each location, and for fresh-market and processing sweet corn.

1. Materials and methods

1.1. General

In 1997 and 1998, three Bt sweet corn hybrids GH 0937, GH 0941, and GH 0943 were evaluated with their non-Bt isolines 'Bonus', 'Empire', and 'Heritage' in small plot trials with multiple locations and planting dates in Illinois, Minnesota, and Wisconsin. For all locations and planting dates, plots were established in a randomized complete block design and consisted of four rows of each hybrid, with 0.76 m row spacing and 3.04 m separating blocks. All treatments were replicated four times per planting date at each location. Evaluations at all locations included counts of *O. nubilalis*, *H. zea*, and *S. frugiperda* in primary ears at harvest. The location, larval instar, and amount of kernel feeding (cm^2) were also assessed for each ear. Ear damage was used to determine the percentage of ears that would be acceptable as fresh-market (no larvae or damage present on ear) and processing produce (damage and/or larvae limited to the tip of the ear with larvae no larger than 1–2 instar). No insecticide applications were made to any of the hybrids during this study.

1.2. Illinois

In 1997, plots were established in southern Illinois at the Dixon Springs Agricultural Center (Simpson, IL) on 31 July, and in the southwest at Collinsville on 9 May and 16 June. In 1998, plots were established at Dixon Springs on 25 June, Collinsville on 8 May, and in central Illinois at Champaign on 2 June. All plantings in 1997 included Bt hybrids GH 0937 and 0943 and their non-Bt isolines 'Bonus' and 'Heritage'. In 1998, plantings included Bt hybrids GH 0937, 0941, and 0943 with their non-Bt isolines 'Bonus', 'Empire', and 'Heritage'. For both years, plots were four rows wide with 0.76 m spacing and rows were 15.2 m long. Plots were harvested in 1997 on 22 October at Dixon Springs and on 25 July and 29 August for the first and second plantings at Collinsville, respectively. Harvest dates for 1998 were 8 September at Dixon Springs, 21 August at Collinsville, and 2 September at Champaign. For each harvest, 25 primary ears were selected at random from the middle two rows of each plot and evaluated for pest presence and damage.

1.3. Minnesota

Plots were established in 1997 and 1998 in southern Minnesota at Rosemount and Waseca. In 1997, planting dates at Rosemount were 22 May and 11 and 23 June; at Waseca, planting dates were 19 May, 10 and 16 June, and 8 July. For the 11 June planting date at Rosemount, 15 consecutive plants in each of the middle two rows of each plot were artificially infested with 10 *H. zea* eggs per plant, and ear evaluations were done on these plants. In 1998, planting dates at Rosemount were 5 May and 1 and 26 June; at Waseca, planting dates were 16 May, 1 and 25 June. For the 5 May planting date at Rosemount, 15 consecutive plants in each of the middle two rows of each plot were artificially infested with 25 *O. nubilalis* eggs per plant and ear evaluations were done on these plants. For both years, plantings included Bt hybrids GH 0937, 0941, and 0943 with their non-Bt isolines 'Bonus', 'Empire', and 'Heritage'. Plots were 4 rows wide with 0.76 m spacing and rows were 9.1 m long. Harvest dates in 1997 at Rosemount were 22 August and 10 and 23 September; at Waseca, harvest dates were 22 August, 10 September (for both the second and third planting), and 1 October. In 1998, harvest dates at Rosemount were 13 and 26 August and 15 September; at Waseca, harvest dates were 14 and 26 August, and 15 September. For each harvest, 25 primary ears were selected at random from the middle two rows of each plot and evaluated for pest presence and damage. In addition to pest evaluations in 1998, 10 ears from each plot were husked and weighed for yield comparisons.

1.4. Wisconsin

Plots were established in 1997 and 1998 in southern Wisconsin at Arlington. In 1997, the planting date was 18 June; in 1998 planting dates were 17 and 26 June. Plantings in 1997 included Bt hybrids GH 0937 and 0943 and their non-Bt isolines 'Bonus' and 'Heritage', and in 1998, included Bt hybrids GH 0937, 0941, and 0943 with their non-Bt isolines 'Bonus', 'Empire', and 'Heritage'. Plots were 4 rows wide with 0.76 m spacing and rows were 11.6 m long. Harvest dates for 1997 and 1998 were 24 September (1997) and 3 and 11 September (1998). At harvest, 20 primary ears in 1997 and 25 primary ears in 1998 were selected at random from the middle two rows of each plot and evaluated for pest presence and damage.

1.5. Data analysis

Data for each year were analyzed using a one-way analysis of variance and the Ryan–Einot–Gabriel–Welsch multiple range test (REGWQ) ($P = 0.05$) for mean separation (SAS Institute, 1995). Insect counts and feeding damage data were transformed using a RANK procedure (non-parametric) to account for the non-normal distribution of data across Bt and non-Bt hybrids. For non-normal populations the multiple comparisons procedure is more robust and has more power when rank-transformed data are used (Conover and Iman, 1981). Data recorded as proportions were transformed using arcsine transformation (SAS Institute, 1995).

Through the use of expected utility analysis (e.g., Carlson, 1970; Moffitt et al., 1983), multiple data sets can be combined to allow for multiple effects, e.g., variable environmental conditions, to be incorporated into a more thorough assessment of the performance of various pest control strategies. A major benefit of this approach is that it allows one to combine multiple data sets with no prior assumptions of homogeneity of variances or of normally distributed data. Data used for expected utility analyses included percent marketable ears and the frequency with which each level of marketability occurred for each category of sweet corn production in each state. From these data the expected utility (the weighted mean using probabilities as weights) and the standard deviation of the expected utility were calculated (e.g., Carlson, 1970). The expected utility for each category in each state was obtained using:

$$E(U) = \sum U(\theta) \cdot P(\theta), \quad (1)$$

where $U(\theta)$ is the payoff (utility) derived from each action and $P(\theta)$ is the probability distribution (Carlson, 1970). Standard deviation (SD) for the expected value was calculated using:

$$\mathrm{SD} = \sqrt{\sum_{x=1}^{n} (A_x - \bar{A})^2 P_x}, \quad (2)$$

where $\bar{A}$ is expected value, A_x is the outcome for the xth possible event, and P_x is the probability of occurrence for that outcome (Shim et al., 1986). In addition, the cumulative frequency (f) of percent marketable ears was calculated for each marketability type, for each state (e.g., Moffitt et al., 1983). To determine the probability of achieving a specific level of marketable ears, these data were plotted using 1-f (WDH, unpublished data).

2. Results

2.1. O. nubilalis

In 1997 and 1998, for most locations and most planting dates, Bt hybrids provided significant control of *O. nubilalis* compared with the non-Bt isolines (Tables 1 and 2). The only exception occurred for early planting dates with low population densities of *O. nubilalis* (Tables 1 and 2), which resulted in minimal damage on non-Bt isolines. For most locations and planting dates, Bt hybrids provided 100% control of *O. nubilalis* infestations. When *O. nubilalis* control was $<100\%$, population densities were still $\leqslant 0.12$ larvae per ear.

Table 1
Mean density of *Ostrinia nubilalis* (ECB), *Helicoverpa zea* (CEW), and *Spodoptera frugiperda* (FAW) per ear in Bt and non-Bt sweet corn, 1997[a]

Location		PD[b]	Variety	ECB total larvae (±SEM)	CEW 1–2 instar (±SEM)	CEW 3–6 instars (±SEM)	FAW total larvae (±SEM)
IL	Dixon Springs	1	0937	0.00±0.00 a	0.00±0.00 b	0.01±0.01 a	0.00±0.00 b
		1	0941	—	—	—	—
		1	0943	0.12±0.12 a	0.02±0.01 b	0.01±0.01 a	0.04±0.04 b
		1	Bonus	0.21±0.10 a	0.05±0.03 ab	0.11±0.09 a	0.28±0.07 a
		1	Empire	—	—	—	—
		1	Heritage	0.48±0.20 a	0.16±0.04 a	0.11±0.06 a	0.23±0.04 a
	Collinsville	1	0937	0.00±0.00 a	0.00±0.00 a	0.03±0.01 a	0.00±0.00 a
		1	0941	—	—	—	—
		1	0943	0.00±0.00 a	0.04±0.02 a	0.04±0.02 a	0.00±0.00 a
		1	Bonus	0.00±0.00 a	0.01±0.01 a	0.04±0.02 a	0.00±0.00 a
		1	Empire	—	—	—	—
		1	Heritage	0.00±0.00 a	0.00±0.00 a	0.01±0.01 a	0.00±0.00 a
		2	0937	0.00±0.00 b	0.00±0.00 c	0.00±0.00 b	0.00±0.00 b
		2	0941	—	—	—	—
		2	0943	0.03±0.02 b	0.23±0.08 b	0.02±0.02 b	0.00±0.00 b
		2	Bonus	0.25±0.07 a	0.44±0.09 a	0.65±0.05 a	0.00±0.00 b
		2	Empire	—	—	—	—
		2	Heritage	0.28±0.02 a	0.50±0.05 a	0.91±0.13 a	0.08±0.03 a
MN	Rosemount	1	0937	0.03±0.03 b	0.00±0.00 a	0.00±0.00 a	—
		1	0941	0.01±0.01 b	0.00±0.00 a	0.00±0.00 a	—
		1	0943	0.04±0.03 b	0.00±0.00 a	0.00±0.00 a	—
		1	Bonus	0.10±0.06 b	0.00±0.00 a	0.00±0.00 a	—
		1	Empire	0.17±0.06 ab	0.00±0.00 a	0.00±0.00 a	—
		1	Heritage	0.42±0.08 a	0.00±0.00 a	0.00±0.00 a	—
		2	0937	0.01±0.01 b	0.04±0.03 ab	0.00±0.00 b	—
		2	0941	0.00±0.00 b	0.02±0.02 b	0.00±0.00 b	—
		2	0943	0.02±0.02 b	0.19±0.08 ab	0.02±0.02 b	—
		2	Bonus	2.46±0.16 a	0.11±0.03 ab	0.49±0.12 a	—
		2	Empire	2.64±0.21 a	0.20±0.06 a	0.47±0.03 a	—
		2	Heritage	2.65±0.30 a	0.12±0.00 ab	0.55±0.02 a	—
		3	0937	0.00±0.00 b	0.03±0.03 b	0.00±0.00 b	—
		3	0941	0.00±0.00 b	0.01±0.01 b	0.00±0.00 b	—
		3	0943	0.00±0.00 b	0.03±0.02 b	0.00±0.00 b	—
		3	Bonus	2.18±0.12 a	0.44±0.07 a	0.62±0.12 a	—
		3	Empire	2.22±0.17 a	0.44±0.13 a	0.58±0.09 a	—
		3	Heritage	2.29±0.26 a	0.33±0.02 a	0.62±0.07 a	—
	Waseca	1	0937	0.02±0.01 b	0.00±0.00 a	0.00±0.00 a	—
		1	0941	0.00±0.00 b	0.00±0.00 a	0.00±0.00 a	—
		1	0943	0.00±0.00 b	0.00±0.00 a	0.00±0.00 a	—
		1	Bonus	0.50±0.10 a	0.00±0.00 a	0.00±0.00 a	—
		1	Empire	0.76±0.12 a	0.00±0.00 a	0.00±0.00 a	—
		1	Heritage	0.60±0.16 a	0.00±0.00 a	0.01±0.01 a	—
		2	0937	0.00±0.00 b	0.10±0.04 c	0.00±0.00 c	—
		2	0941	0.00±0.00 b	0.20±0.09 c	0.00±0.00 c	—
		2	0943	0.00±0.00 b	0.23±0.03 bc	0.00±0.00 c	—
		2	Bonus	3.66±0.48 a	0.69±0.11 a	0.75±0.12 a	—
		2	Empire	4.07±0.17 a	0.52±0.09 ab	0.55±0.03 b	—
		2	Heritage	3.66±0.20 a	0.34±0.10 abc	0.73±0.05 a	—
		3	0937	0.00±0.00 b	0.19±0.05 c	0.00±0.00 b	—
		3	0941	0.01±0.01 b	0.08±0.04 c	0.01±0.01 b	—
		3	0943	0.00±0.00 b	0.27±0.04 bc	0.01±0.01 b	—
		3	Bonus	4.30±0.35 a	0.75±0.19 ab	0.66±0.23 a	—
		3	Empire	4.47±0.08 a	1.03±0.06 a	0.46±0.06 a	—
		3	Heritage	4.29±0.47 a	0.66±0.08 ab	0.77±0.10 a	—

(*Table continued on next page*)

Table 1 (*continued*)

Location		PD[b]	Variety	ECB total larvae (±SEM)	CEW 1–2 instar (±SEM)	CEW 3–6 instars (±SEM)	FAW total larvae (±SEM)
		4	0937	0.00±0.00 c	0.02±0.02 b	0.00±0.00 b	—
		4	0941	0.00±0.00 c	0.03±0.02 b	0.00±0.00 b	—
		4	0943	0.00±0.00 c	0.07±0.02 ab	0.00±0.00 b	—
		4	Bonus	3.19±0.15 a	0.16±0.02 a	0.63±0.07 a	—
		4	Empire	3.51±0.21 a	0.20±0.05 a	0.50±0.04 a	—
		4	Heritage	2.23±0.14 b	0.16±0.07 a	0.62±0.05 a	—
WI	Arlington	1	0937	0.00±0.00 c	0.00±0.00 a	0.00±0.00 b	—
		1	0941	—	—	—	—
		1	0943	0.00±0.00 c	0.00±0.00 a	0.00±0.00 b	—
		1	Bonus	1.62±0.13 b	0.03±0.02 a	0.22±0.07 a	—
		1	Empire	—	—	—	—
		1	Heritage	1.99±0.09 a	0.00±0.00 a	0.27±0.07 a	—

[a] Means within columns followed by the same letter are not significantly different based on ANOVA and Ryan-Einot-Gabriel-Welsch multiple range test (REGWQ) ($P \leqslant 0.05$). Data were transformed using the rank transformation for insect counts; untransformed means are presented.
[b] PD = Planting date

Table 2
Mean density of *Ostrinia nubilalis* (ECB), *Helicoverpa zea* (CEW), and *Spodoptera frugiperda* (FAW) per ear in Bt and non-Bt sweet corn, 1998[a]

Location		PD[b]	Variety	ECB total larvae	CEW 1–2 instar	CEW 3–6 instars	FAW total larvae
IL	Dixon Springs	1	0937	0.09±0.08 bc	0.00±0.00 a	0.00±0.00 a	—
		1	0941	0.00±0.00 c	0.00±0.00 a	0.00±0.00 a	—
		1	0943	0.07±0.07 c	0.00 ±0.00 a	0.00±0.00 a	—
		1	Bonus	0.58±0.09 a	0.00±0.00 a	0.00±0.00 a	—
		1	Empire	0.65±0.14 a	0.00±0.00 a	0.00±0.00 a	—
		1	Heritage	0.39±0.16 ab	0.00±0.00 a	0.00±0.00 a	—
	Collinsville	1	0937	0.00±0.00 a	0.08±0.06 a	0.02±0.01 b	0.05±0.03 a
		1	0941	0.00±0.00 a	0.02±0.01 a	0.01±0.01 b	0.00±0.00 a
		1	0943	0.01±0.01 a	0.00±0.00 a	0.16±0.08 a	0.06±0.03 a
		1	Bonus	0.00±0.00 a	0.03±0.03 a	0.01±0.01 b	0.02±0.01 a
		1	Empire	0.02±0.02 a	0.04±0.02 a	0.10±0.04 ab	0.01±0.01 a
		1	Heritage	0.00±0.00 a	0.03±0.02 a	0.19±0.07 a	0.03±0.01 a
	Champaign	1	0937	0.01±0.01 b	0.10±0.06 a	0.00±0.00 b	0.00±0.00 b
		1	0941	0.02±0.01 ab	0.00±0.00 a	0.07±0.03 ab	0.01±0.01 ab
		1	0943	0.02±0.02 ab	0.07±0.03 a	0.02±0.02 b	0.00±0.00 b
		1	Bonus	0.19±0.07 ab	0.07±0.02 a	0.14±0.06 ab	0.01±0.01 ab
		1	Empire	0.25±0.14 ab	0.04±0.02 a	0.33±0.03 a	0.05±0.02 a
		1	Heritage	0.28±0.10 a	0.12±0.05 a	0.31±0.11 a	0.02±0.02 ab
MN	Rosemount	1	0937	0.00±0.00 d	0.00±0.00 a	0.00±0.00 a	—
		1	0941	0.00±0.00 d	0.00±0.00 a	0.00±0.00 a	—
		1	0943	0.00±0.00 d	0.00±0.00 a	0.00±0.00 a	—
		1	Bonus	2.48±0.35 a	0.00±0.00 a	0.00±0.00 a	—
		1	Empire	1.72±0.37 b	0.00±0.00 a	0.00±0.00 a	—
		1	Heritage	0.75±0.09 c	0.00±0.00 a	0.00±0.00 a	—
		2	0937	0.00±0.00 a	0.00±0.00 a	0.00±0.00 a	—
		2	0941	0.00±0.00 a	0.00±0.00 a	0.00±0.00 a	—
		2	0943	0.00±0.00 a	0.00±0.00 a	0.00±0.00 a	—
		2	Bonus	0.10±0.07 a	0.00±0.00 a	0.00±0.00 a	—
		2	Empire	0.06±0.03 a	0.00±0.00 a	0.01±0.01 a	—
		2	Heritage	0.03±0.02 a	0.01±0.01 a	0.00±0.00 a	—
		3	0937	0.00±0.00 c	0.22±0.06 a	0.01±0.01 c	—
		3	0941	0.00±0.00 c	0.26±0.06 a	0.00±0.00 c	—

(*Table continued on next page*)

Table 2 (*continued*)

Location		PD[b]	Variety	ECB total larvae	CEW 1–2 instar	CEW 3–6 instars	FAW total larvae
		3	0943	0.00±0.00 c	0.10±0.03 a	0.00±0.00 c	—
		3	Bonus	0.10±0.03 a	0.08±0.04 a	1.59±0.12 a	—
		3	Empire	0.04±0.02 ab	0.29±0.07 a	1.25±0.08 b	—
		3	Heritage	0.02±0.01 b	0.19±0.08 a	1.46±0.10 ab	—
	Waseca	1	0937	0.00±0.00 a	0.00±0.00 a	0.00±0.00 a	—
		1	0941	0.00±0.00 a	0.00±0.00 a	0.00±0.00 a	—
		1	0943	0.00±0.00 a	0.00±0.00 a	0.00±0.00 a	—
		1	Bonus	0.02±0.02 a	0.01±0.01 a	0.00±0.00 a	—
		1	Empire	0.00±0.00 a	0.00±0.00 a	0.01±0.01 a	—
		1	Heritage	0.04±0.02 a	0.00±0.00 a	0.01±0.01 a	—
		2	0937	0.00±0.00 b	0.01±0.01 a	0.00±0.00 a	—
		2	0941	0.00±0.00 b	0.00±0.00 a	0.00±0.00 a	—
		2	0943	0.00±0.00 b	0.00±0.00 a	0.00±0.00 a	—
		2	Bonus	0.31±0.11 a	0.01±0.01 a	0.00±0.00 a	—
		2	Empire	0.24±0.12 a	0.01±0.01 a	0.01±0.01 a	—
		2	Heritage	0.36±0.09 a	0.02±0.01 a	0.00±0.00 a	—
		3	0937	0.00±0.00 c	0.18±0.05 a	0.00±0.00 c	—
		3	0941	0.00±0.00 c	0.32±0.06 a	0.00±0.00 c	—
		3	0943	0.00±0.00 c	0.42±0.06 a	0.00±0.00 c	—
		3	Bonus	0.24±0.03 a	0.27±0.06 a	1.26±0.22 a	—
		3	Empire	0.13±0.03 b	0.30±0.09 a	1.01±0.10 b	—
		3	Heritage	0.13±0.04 b	0.28±0.04 a	1.25±0.03 ab	—
WI	Arlington	1	0937	0.00±0.00 a	0.00±0.00 b	0.00±0.00 b	0.00±0.00 a
		1	0941	0.00±0.00 a	0.00±0.00 b	0.00±0.00 b	0.00±0.00 a
		1	0943	0.00±0.00 a	0.00±0.00 b	0.00±0.00 b	0.00±0.00 a
		1	Bonus	0.10±0.05 a	0.21±0.06 a	0.23±0.08 a	0.00±0.00 a
		1	Empire	0.04±0.04 a	0.10±0.08 ab	0.13 ±0.05 a	0.00±0.00 a
		1	Heritage	0.05±0.05 a	0.10±0.02 a	0.24 ±0.06 a	0.04±0.02 a
		2	0937	0.01±0.01 a	0.00±0.00 b	0.00±0.00 c	0.00±0.00 a
		2	0941	0.00±0.00 a	0.00±0.00 b	0.00±0.00 c	0.00±0.00 a
		2	0943	0.00±0.00 a	0.00±0.00 b	0.00±0.00 c	0.01±0.01 a
		2	Bonus	0.00±0.00 a	0.14±0.05 a	1.05±0.10 a	0.00±0.00 a
		2	Empire	0.01±0.01 a	0.21±0.07 a	1.01±0.11 a	0.00±0.00 a
		2	Heritage	0.03±0.03 a	0.28±0.09 a	0.66±0.09 b	0.00±0.00 a

[a] Means within columns followed by the same letter are not significantly different based on ANOVA and Ryan-Einot-Gabriel-Welsch multiple range test (REGWQ) ($P \leqslant 0.05$). Data were transformed using the rank transformation for insect counts; untransformed means are presented.
[b] PD = Planting date.

2.2. *H. zea*

For 3–6 instar *H. zea*, Bt hybrids for all planting dates at all locations provided significant control, compared with non-Bt isolines, except where populations were low (Tables 1 and 2). However, for both years, few locations and planting dates indicated consistent significant control of 1–2 instar *H. zea* for Bt hybrids compared with non-Bt isolines (Tables 1 and 2). For 1997, Collinsville, IL, planting date 2; Rosemount, MN planting date 3; and Waseca, MN planting dates 3 and 4, indicated that Bt hybrids provided significant control of 1–2 instar *H. zea*. In 1998, only the Arlington, WI planting dates showed Bt hybrids providing significant control of 1–2 instar *H. zea*.

2.3. *S. frugiperda*

S. frugiperda was observed at relatively low infestation levels in Illinois in 1997 and 1998 and in Wisconsin in 1998. For all planting dates, at all locations, *S. frugiperda* populations never exceeded 0.28 larvae per ear in the non-Bt isolines (Tables 1 and 2). For 1997, in Illinois, *S. frugiperda* was observed in all planting dates at all locations, and in 1998, at Collinsville and Champaign locations. Bt hybrids provided significant control of *S. frugiperda* at the Dixon Springs location in 1997 compared with their non-Bt isolines (Tables 1 and 2). However, for all other locations and planting dates for both years, where population densities were low, no significant differences were observed. For 1998, in

Table 3
Percent marketable ears for Bt and non-Bt sweet corn hybrids exposed to infestations of *Ostrinia nubilalis*, *Helicoverpa zea*, and *Spodoptera frugiperda*, 1997[a]

Location		PD[b]	Variety	Damage per ear (cm^2)	Fresh market (%)	Processing (%)
IL	Dixon Springs	1	0937	0.10±0.06 b	99±1.00 a	100±0.00 a
		1	0941	—	—	—
		1	0943	0.17±0.14 b	98±2.00 a	100±0.00 a
		1	Bonus	2.45±0.18 a	25±7.55 b	64±9.93 b
		1	Empire	—	—	—
		1	Heritage	4.89±0.39 a	17±4.12 b	38±6.22 c
	Collinsville	1	0937	0.11±0.02 b	60±4.32 a	98±1.15 a
		1	0941	—	—	—
		1	0943	0.14±0.07 b	69±6.61 a	92±3.65 a
		1	Bonus	0.93±0.21 a	27±9.57 a	94±2.58 a
		1	Empire	—	—	—
		1	Heritage	3.39±0.28 a	26±19.90a	95±1.91 a
		2	0937	0.08±0.01 c	70±9.02 a	100±0.00 a
		2	0941	—	—	—
		2	0943	0.22±0.09 c	59±14.91a	87±13.00a
		2	Bonus	4.93±0.89 b	2±1.15 b	38±4.76 b
		2	Empire	—	—	—
		2	Heritage	9.00±0.44 a	0±0.00 b	29±5.51 b
MN	Rosemount	1	0937	0.00±0.00 a	97±3.00 a	100±0.00 a
		1	0941	0.00±0.00 a	98±1.15 a	100±0.00 a
		1	0943	0.00±0.00 a	96±2.83 a	100±0.00 a
		1	Bonus	0.00±0.00 a	91±5.74 ab	99±1.00 a
		1	Empire	0.00±0.00 a	84±4.62 ab	98±2.00 a
		1	Heritage	0.00±0.00 a	74±4.76 b	95±3.00 a
		2	0937	0.00±0.00 b	93±4.43 a	100±0.00 a
		2	0941	0.00±0.00 b	98±2.00 a	100±0.00 a
		2	0943	0.02±0.01 b	82±4.76 b	98±2.00 a
		2	Bonus	0.41±0.09 a	0±0.00 c	12±3.65 b
		2	Empire	0.48±0.02 a	1±1.00 c	7±2.52 b
		2	Heritage	0.50±0.05 a	0±0.00 c	6±2.00 b
		3	0937	0.00±0.0.00 b	96±2.83 a	100±0.00 a
		3	0941	0.00±0.0.00 b	95±2.52 a	100±0.00 a
		3	0943	0.00±0.0.00 b	89±5.51 a	100±0.00 a
		3	Bonus	0.54±0.04 a	0±0.00 b	1±1.00 b
		3	Empire	0.51±0.05 a	0±0.00 b	3±1.00 b
		3	Heritage	0.54±0.02 a	0±0.00 b	1±1.00 b
	Waseca	1	0937	0.00±0.00 a	97±1.91 a	100±0.00 a
		1	0941	0.00±0.00 a	99±1.00 a	100±0.00 a
		1	0943	0.00±0.00 a	98±1.15 a	100±0.00 a
		1	Bonus	0.00±0.00 a	65±6.61 b	89±1.00 b
		1	Empire	0.00±0.00 a	57±5.26 b	85±5.00 b
		1	Heritage	0.00±0.00 a	66±6.22 b	92±3.65 b
		2	0937	0.00±0.00 b	91±3.42 a	100±0.00 a
		2	0941	0.00±0.00 b	85±5.51 a	100±0.00 a
		2	0943	0.00±0.00 b	82±4.76 a	100±0.00 a
		2	Bonus	0.57±0.04 a	0±0.00 b	0±0.00 b
		2	Empire	0.59±0.06 a	0±0.00 b	1±1.00 b
		2	Heritage	0.58±0.03 a	0±0.00 b	0±0.00 b
		3	0937	0.00±0.00 b	86±6.22 a	100±0.00 a
		3	0941	0.00±0.00 b	84±2.31 a	99±1.00 a
		3	0943	0.01±0.00 b	80±3.65 a	99±1.00 a
		3	Bonus	0.51±0.01 a	0±0.00 b	0±0.00 b

(*Table continued on next page*)

Table 3 (*continued*)

Location		PD[b]	Variety	Damage per ear (cm^2)	Fresh market (%)	Processing (%)
		3	Empire	0.46±0.03 a	0±0.00 b	0±0.00 b
		3	Heritage	0.52±0.04 a	0±0.00 b	0±0.00 b
		4	0937	0.00±0.00 c	98±2.00 a	100±0.00 a
		4	0941	0.01±0.01 c	97±1.91 a	100±0.00 a
		4	0943	0.01±0.01 c	96±4.00 a	98±2.00 a
		4	Bonus	0.78±0.03 a	0±0.00 b	0±0.00 b
		4	Empire	0.63±0.02 ab	0±0.00 b	2±1.15 b
		4	Heritage	0.60±0.03 b	0±0.00 b	2±1.15 b
WI	Arlington	1	0937	0.00±0.00 b	100±0.00 a	100±0.00 a
		1	0941	—	—	—
		1	0943	0.00±0.00 b	100±0.00 a	100±0.00 a
		1	Bonus	2.72±0.73 a	19±3.00 b	24±1.63 b
		1	Empire	—	—	—
		1	Heritage	3.52±0.56 a	11±1.91 c	13±2.52 c

[a] Means within columns followed by the same letter are not significantly different based on ANOVA and Ryan-Einot-Gabriel-Welsch multiple range test (REGWQ) ($P \leqslant 0.05$). Data were transformed by arcsine for proportions; untransformed means are presented.
[b] PD = Planting date.

Wisconsin, *S. frugiperda* was observed in both planting dates; however, no significant control was provided by the Bt hybrids (Tables 1 and 2).

2.4. Percent marketable ears/yield

For both years, and all locations, hybrids with the lowest at-harvest larval infestations (Tables 1 and 2) had the highest percentage of marketable ears (Tables 3 and 4). Damage per ear was very low for the non-Bt hybrids, and usually $<5\,cm^2$ if the damage was caused primarily by *O. nubilalis*. However, damage ranged from 5 to $38\,cm^2$ for unusually high *O. nubilalis* infestations, or if *H. zea* and *S. frugiperda* were present. For both years, all planting dates, and at all locations, Bt hybrids consistently resulted in significantly less damage per ear and provided significantly higher percentages of marketable ears (both fresh-market sale and processing), compared with non-Bt isolines (Tables 3 and 4). Exceptions occurred in 1997, in the first planting date of Collinsville and Rosemount (Table 3), and in 1998, at Collinsville, the second planting date at Rosemount, and the first planting date at Waseca (Table 4), where larval densities and damage per ear were low. Percent marketable ears for fresh-market were always lower than for processing, and for some non-Bt isolines all harvested ears were unmarketable. For fresh-market and processing ears, percent marketable ears typically ranged from 70–100% and 90–100%, respectively (Tables 3 and 4).

In 1998, at Rosemount and Waseca MN locations, Bt hybrids provided, in most cases, significant increases in marketable yield for fresh-market and processing sweet corn production compared with non-Bt isolines (Table 5). Processing yields were never lower and typically higher than fresh-market yields. Under heavy pest infestations, yield suitable for fresh-market sale decreased to zero. The opposite occurred under low pest pressure with no significant difference between Bt and non-Bt isolines, which typically occurred for early planting dates.

2.5. Expected utility

Results for expected utility of Bt hybrids compared with non-Bt isolines indicate that Bt hybrids provide a very high expected utility (percent marketable ears), for both fresh-market and processing, with much less variability (SD) (Table 6). Given the low SD for the Bt hybrids, coefficients of variation (CV) were also very low, averaging 0.17 and 0.05 for all three states combined, for fresh-market and processing, respectively. Bt hybrids provided 75–99% and 94–99% expected marketable ears for fresh-market and processing, respectively. Non-Bt isolines provided 14–34% and 41–56% marketable ears for fresh-market and processing, respectively. Bt hybrids provided a much higher probability of achieving a higher percentage of marketable ears for both fresh-market and processing (Fig. 1). Bt hybrids provided a minimum of 22 and 66% marketable ears for fresh-market and processing, respectively, with a probability of 100%. Moreover, a 70% marketability level can be achieved with a probability of $\geqslant 75\%$ for both fresh-market and processing. To achieve $>60\%$ marketable ears using non-Bt isolines, probability drops below 50% for both fresh-market and processing (Fig. 1). For processing sweet corn, and despite variable pest pressure, data for Minnesota and Wisconsin shows $\geqslant 95\%$ probability of

Table 4
Percent marketable ears for Bt and non-Bt sweet corn hybrids exposed to infestations of *Ostrinia nubilalis*, *Helicoverpa zea*, and *Spodoptera frugiperda*, 1998[a]

Location		PD[b]	Variety	Damage per ear (cm^2)	Fresh market (%)	Processing (%)
IL	Dixon Springs	1	0937	0.17±0.08 b	89±3.42 b	95±3.00 a
		1	0941	0.00±0.00 b	100±0.00 a	100±0.00 a
		1	0943	0.32±0.19 b	90±4.76 b	96±2.83 a
		1	Bonus	12.14±1.63 a	0±0.00 c	22±5.35 b
		1	Empire	11.95±2.48 a	0±0.00 c	23±7.00 b
		1	Heritage	11.18±2.40 a	13±13.00c	28±11.78b
	Collinsville	1	0937	2.28±1.50 a	55±20.81 a	94±2.58 abc
		1	0941	0.93±0.39 a	73±9.85 a	92±6.69 ab
		1	0943	5.18±1.58 a	22±15.66 a	66±8.00 c
		1	Bonus	3.13±1.75 a	43±18.42 a	98±1.18 a
		1	Empire	2.61±0.91 a	33±22.88 a	79±7.55 abc
		1	Heritage	4.97±0.57 a	7±3.38 a	73±3.98 bc
	Champaign	1	0937	0.13±0.09 b	89±6.19 a	99±1.00 a
		1	0941	0.19±0.09 b	78±8.87 a	95±1.91 a
		1	0943	0.28±0.10 b	77±7.76 a	96±2.83 a
		1	Bonus	1.53±0.36 a	13±3.42 b	71±4.43 b
		1	Empire	2.99±0.80 a	6±2.03 b	56±5.18 b
		1	Heritage	4.03±0.94 a	9±2.12 b	45±7.76 b
MN	Rosemount	1	0937	0.00±0.00 c	100±0.00 a	100±0.00 a
		1	0941	0.00±0.00 c	100±0.00 a	100±0.00 a
		1	0943	0.00±0.00 c	100±0.00 a	100±0.00 a
		1	Bonus	7.66±1.65 a	28±4.32 c	28±4.32 c
		1	Empire	5.71±1.46 ab	28±10.07c	33±8.06 c
		1	Heritage	3.00±0.22 b	50±6.22 b	57±5.74 b
		2	0937	0.00±0.00 a	100±0.00 a	100±0.00 a
		2	0941	0.00±0.00 a	100±0.00 a	100±0.00 a
		2	0943	0.00±0.00 a	100±0.00 a	100±0.00 a
		2	Bonus	0.03±0.02 a	95±3.00 a	97±1.91 a
		2	Empire	0.08±0.06 a	93±3.42 a	98±1.15 a
		2	Heritage	0.11±0.06 a	94±3.46 a	98±1.15 a
		3	0937	0.27±0.20 b	82±6.22 ab	99±1.00 a
		3	0941	0.39±0.10 b	76±1.63 b	100±0.00 a
		3	0943	0.06±0.04 b	88±3.27 a	99±1.00 a
		3	Bonus	28.87±1.94 a	0±0.00 c	3±1.91 b
		3	Empire	24.36±1.66 a	1±1.00 c	10±2.58 b
		3	Heritage	25.00±0.56 a	1±1.00 c	8±3.65 b
	Waseca	1	0937	0.00±0.00 b	100±0.00 a	100±0.00 a
		1	0941	0.00±0.00 b	100±0.00 a	100±0.00 a
		1	0943	0.00±0.00 b	100±0.00 a	100±0.00 a
		1	Bonus	0.12±0.05 a	95±1.00 b	99±1.00 a
		1	Empire	0.12±0.05 a	94±2.00 b	99±1.00 a
		1	Heritage	0.05±0.04 ab	97±1.91 ab	98±1.15 a
		2	0937	0.00±0.00 c	99±1.00 a	100±0.00 a
		2	0941	0.03±0.03 c	99±1.00 a	100±0.00 a
		2	0943	0.00±0.00 c	100±0.00 a	100±0.00 a
		2	Bonus	0.25±0.08 b	73±8.06 b	81±6.81 b
		2	Empire	0.33±0.13 b	79±5.74 b	90±4.76 b
		2	Heritage	0.78±0.18 a	66±3.46 b	81±4.43 b
		3	0937	0.09±0.06 c	83±2.52 a	100±0.00 a
		3	0941	0.21±0.10 c	70±6.22 ab	100±0.00 a
		3	0943	0.12±0.05 c	63±4.43 b	100±0.00 a
		3	Bonus	38.37±1.44 a	0±0.00 c	10±2.58 b

(*Table continued on next page*)

Table 4 (*continued*)

Location		PD[b]	Variety	Damage per ear (cm^2)	Fresh market (%)	Processing (%)
		3	Empire	29.40±2.99 b	1±1.00 c	19±4.43 b
		3	Heritage	34.49±1.93 ab	0±0.00 c	11±2.52 b
WI	Arlington	1	0937	0.00±0.00 c	100±0.00 a	100±0.00 a
		1	0941	0.00±0.00 c	100±0.00 a	100±0.00 a
		1	0943	0.00±0.00 c	100±0.00 a	100±0.00 a
		1	Bonus	1.03±0.28 a	56±9.44 b	73±4.79 c
		1	Empire	0.25±0.10 b	78±8.54 b	90±4.56 b
		1	Heritage	0.90±0.23 a	60±8.66 b	69±6.25 c
		2	0937	0.00±0.00 b	100±0.00 a	100±0.00 a
		2	0941	0.00±0.00 b	100±0.00 a	100±0.00 a
		2	0943	0.05±0.05 b	99±1.25 a	99±1.25 a
		2	Bonus	3.83±0.08 a	11±1.25 b	26±10.08 b
		2	Empire	3.28±0.41 a	10±3.54 b	20±2.04 b
		2	Heritage	2.78±0.40 a	19±5.15 b	31±8.00 b

[a] Means within columns followed by the same letter are not significantly different based on ANOVA and Ryan–Einot–Gabriel–Welsch multiple range test (REGWQ) ($P \leqslant 0.05$). Data were transformed by arcsine for proportions; untransformed means are presented.
[b] PD = Planting date.

achieving >95% marketable ears (Fig. 1); for Illinois, Fig. 1 illustrates ⩾90% probability of achieving >90% marketable ears without the use of foliar insecticides.

3. Discussion

In response to variable planting dates, geographical locations, and in some cases, artificial infestations, a wide range of pest densities were established for use in evaluating efficacy of several Bt sweet corn hybrids. Over the two-year trial, densities for *O. nubilalis*, *H. zea*, and *S. frugiperda* ranged from 0–4.47, 0–1.67, and 0–0.28 larvae per ear, respectively. These density ranges provided a good representation of larval densities typically encountered in sweet corn in the Midwestern US. (e.g., Bartels et al., 1995, Burkness et al., 2001). Clearly, under higher pest pressure, Bt sweet corn hybrids provided significant protection compared with each respective non-Bt isoline. The protection provided by Bt hybrids resulted in fewer pests per ear, less feeding damage per ear, and therefore, higher yield and percentages of marketable ears for both fresh-market and processing (Tables 1–5). However, non-Bt isolines performed just as well as Bt hybrids when pest pressure was low.

As shown in a previous Minnesota study (Burkness et al., 2001), lower marketability for some Bt hybrids may occur due to the influence of *H. zea* and *S. frugiperda* damage. This may explain the lower marketability for some Bt hybrids in Illinois. However, our results are in agreement with Lynch et al. (1999b), where the Bt hybrid GH 0937 performed well against both pests. *H. zea* and *S. frugiperda* larvae may survive on Bt hybrids but there are fitness costs associated with survival. Lynch et al. (1999a) reported that *H. zea* larvae found surviving on Bt sweet corn were generally lethargic, had usually ceased feeding, and had lost weight when compared with average weights of larvae that had fed on non-Bt sweet corn. Lynch et al. (1999a) also found that *S. frugiperda* survival was reduced on Bt sweet corn but not to the extent of *H. zea*. However, in most cases *H. zea* found in the Bt hybrids were limited to first or second instars (Tables 1 and 2), which are removed early in the processing plant by husking and washing equipment and are rarely a contaminant concern (e.g., Bartels et al., 1995).

Given the fact that we cannot predict pest densities in sweet corn each year, concern focuses on how consistently Bt hybrids perform over several years in different geographic locations with different pest complexes and pest densities. Specifically, what is the probability of pest control or product marketability provided by Bt hybrids under a variety of pest densities and environmental conditions? We illustrate the probability of achieving specified marketability levels for all 3 states for fresh-market and processing. For Minnesota and Wisconsin, expected utility analysis indicates a high probability (>95%) of the Bt hybrids providing a high percentage (>95%) of processing marketable ears. Although the probability is slightly less for Illinois, due to the presence of *H. zea* and *S. frugiperda*, our results show a minimum 90% probability of achieving 90% or more marketable ears for processing. This is also demonstrated with Bt hybrids having a much higher expected utility for marketable ears and a much lower standard deviation and coefficient of variation. This suggests that Bt

Table 5
Yield response of Bt and non-Bt sweet corn hybrids exposed to infestations of *Ostrinia nubilalis* and *Helicoverpa zea*, Rosemount, MN, 1998[a]

Location		PD[c]	Variety	Yield/10 ears (kg)	Yield (metric ton/ha)[d]	Marketable yield (metric ton/ha)[b]	
						Fresh-market	Processing
MN	Rosemount	1	0937	2.20±0.10 a	13.11±0.58 a	13.11±0.58 a	13.11±0.58 a
		1	0941	2.59±0.08 a	15.46±0.45 a	15.46±0.45 a	15.46±0.45 a
		1	0943	2.51±0.05 a	15.01±0.31 a	15.01±0.31 a	15.01±0.31 a
		1	Bonus	2.48±0.06 a	14.81±0.36 a	4.12±0.58 c	4.12±0.58 c
		1	Empire	2.48±0.13 a	14.81±0.76 a	3.97±1.23 c	4.75±0.94 c
		1	Heritage	2.62±0.13 a	15.68±0.78 a	7.91±1.19 b	9.03±1.21 b
		2	0937	1.85±0.04 b	11.07±0.20 b	11.07±0.20 c	11.07±0.20 b
		2	0941	2.32±0.03 a	13.84±0.20 a	13.84±0.20 a	13.84±0.20 a
		2	0943	2.23±0.07 a	13.31±0.40 a	13.31±0.40 a	13.31±0.40 a
		2	Bonus	2.01±0.09 b	12.01±0.52 b	11.43±0.72 bc	11.65±0.60 b
		2	Empire	2.30±0.06 a	13.69±0.36 a	12.72±0.49 ab	13.42±0.31 a
		2	Heritage	2.31±0.04 a	13.80±0.20 a	12.95±0.36 a	13.51±0.09 a
		3	0937	2.07±0.06 b	12.37±0.36 b	10.10±0.67 b	12.23±0.36 b
		3	0941	2.42±0.12 a	14.43±0.72 a	10.93±0.43 ab	14.43±0.72 a
		3	0943	2.26±0.09 ab	13.51±0.52 ab	11.87±0.52 a	13.37±0.56 ab
		3	Bonus	2.14±0.04 ab	12.75±0.22 ab	0.00±0.00 c	0.38±0.25 c
		3	Empire	2.07±0.08 b	12.34±0.49 b	0.11±0.11 c	1.21±0.29 c
		3	Heritage	2.34±0.05 ab	13.96±0.27 ab	0.13±0.13 c	1.10±0.52 c
	Waseca	1	0937	2.34±0.07 b	13.93±0.40 b	13.93±0.40 b	13.93±0.40 b
		1	0941	2.92±0.05 a	17.45±0.27 a	17.45±0.27 a	17.45±0.27 a
		1	0943	2.72±0.05 a	16.24±0.31 a	16.24±0.31 a	16.24±0.31 a
		1	Bonus	2.36±0.08 b	14.11±0.47 b	13.42±0.56 b	13.98±0.58 b
		1	Empire	2.83±0.12 a	16.91±0.72 a	15.86±0.54 a	16.73±0.65 a
		1	Heritage	2.93±0.09 a	17.50±0.52 a	17.00±0.81 a	17.16±0.67 a
		2	0937	1.74±0.06 c	10.37±0.34 c	10.28±0.38 c	10.37±0.34 c
		2	0941	2.35±0.07 ab	14.05±0.40 ab	13.89±0.29 a	14.05±0.40 a
		2	0943	2.16±0.05 ab	12.88±0.27 ab	12.88±0.27 ab	12.88±0.27 ab
		2	Bonus	2.04±0.12 b	12.19±0.67 b	8.89±1.12 c	9.86±0.94 c
		2	Empire	2.37±0.06 a	14.16±0.36 a	11.16±0.74 bc	12.75±0.78 ab
		2	Heritage	2.42±0.09 a	14.43±0.54 a	9.52±0.60 c	11.65±0.63 bc
		3	0937	1.82±0.07 abc	10.87±0.43 abc	8.98±0.20 a	10.87±0.43 ab
		3	0941	2.05±0.04 ab	12.23±0.22 ab	8.58±0.87 a	12.23±0.22 a
		3	0943	1.66±0.13 bc	9.92±0.76 bc	6.27±0.76 b	9.92±0.76 b
		3	Bonus	1.61±0.09 c	9.63±0.58 c	0.00±0.00 c	0.94±0.25 c
		3	Empire	2.09±0.16 a	12.48±0.94 a	0.13±0.13 c	2.42±0.63 c
		3	Heritage	2.03±0.18 ab	12.14±1.05 ab	0.00±0.00 c	1.37±0.31 c

[a] Means within columns followed by the same letter are not significantly different based on ANOVA and Ryan-Einot-Gabriel-Welsch multiple range test (REGWQ) ($P9 \leqslant 0.05$). Data were transformed by arcsine for proportions; untransformed means are presented.
[b] metric ton/hectare calculated using a plant density of 59,280/hectare.
[c] PD = Planting date.
[d] Marketable yield calculated using percentage of marketable ears for fresh-market and processing (Table 4) and calculated yield in metric ton/hectare.

hybrids can provide a high level of marketable ears with minimal production risk. In Illinois, Bt hybrids provided much higher levels of marketable ears for fresh-market and processing than the non-Bt isolines, even though pest infestations start much earlier and can include high levels of all three Lepidopteran pests. Overall, when different environmental conditions, pest densities, and pest complexes are combined, Bt hybrids provided approximately a 3-fold (fresh-market) and 2-fold (processing) increase in marketable ears over the non-Bt isolines, with a 2–5-fold decrease in standard deviation (production risk).

In summary, the protection provided by Bt sweet corn hybrids is equal to or exceeds that of conventional insecticide use in the Midwestern U.S. (e.g., Bartels et al., 1995). In addition, Bt sweet corn hybrids provide a high level of control with minimal variability. Examining the performance of Bt hybrids across different geographical locations and under different pest complexes and densities, allows for an assessment of the benefit Bt

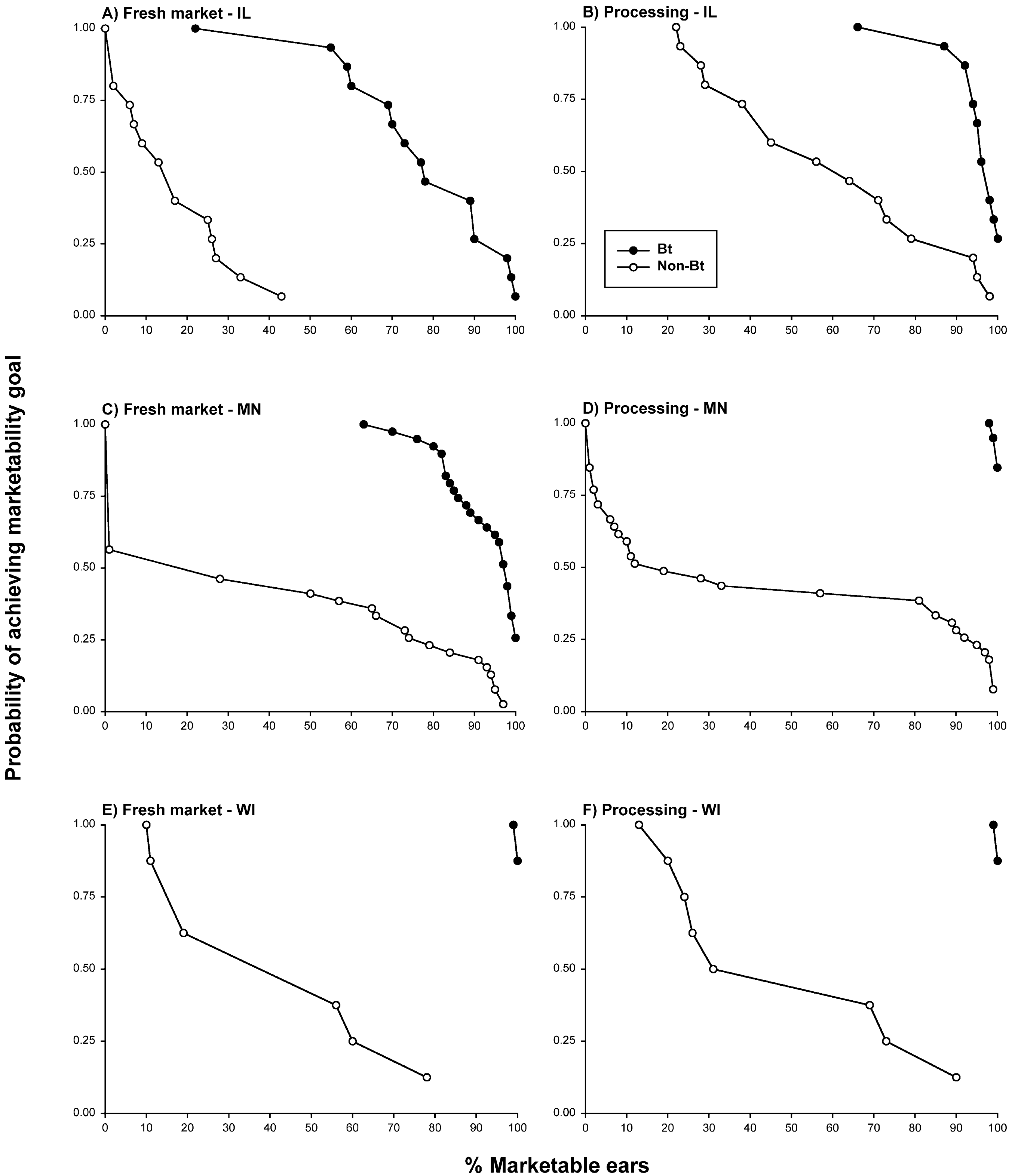

Fig. 1. Probability of achieving specified levels of percent marketable ears for fresh-market and processing sweet corn production systems using Bt and non-Bt hybrids in Illinois (A and B), Minnesota (C and D), and Wisconsin (E and F).

sweet corn can provide. Given the expected utility analysis, Bt sweet corn provides consistent and less risky control of lepidopteran pests. To complete the analysis, the addition of commonly used insecticide treatment regimes and the economics of each strategy should be included.

Table 6
Expected utility, risk (standard deviation), coefficient of variation for Bt and non-Bt sweet corn marketability (%), for fresh-market and processing in Illinois, Minnesota, and Wisconsin, 1997–1998

Location	Marketability category/hybrid	Expected utility (%)[a]	Risk (SD)[a]	CV[a]
Illinois ($n=18$)	Fresh-market/Bt	75.20	20.19	0.27
	Fresh-market/non-Bt	14.73	12.93	0.88
	Processing/Bt	94.00	8.31	0.09
	Processing/non-Bt	56.87	26.27	0.46
Minnesota ($n=39$)	Fresh-market/Bt	92.23	9.26	0.10
	Fresh-market/non-Bt	34.18	39.50	1.16
	Processing/Bt	99.79	0.52	0.005
	Processing/non-Bt	41.36	42.52	1.03
Wisconsin ($n=9$)	Fresh-market/Bt	99.88	0.33	0.003
	Fresh-market/non-Bt	33.00	25.43	0.77
	Processing/Bt	99.88	0.33	0.003
	Processing/non-Bt	43.25	27.40	0.63
Total (3 states) ($n=66$)	Fresh-market/Bt	89.10	14.85	0.17
	Fresh-market/non-Bt	29.32	34.26	1.17
	Processing/Bt	98.40	4.80	0.05
	Processing/non-Bt	45.35	37.99	0.84

[a] Expected utility ($E(U)$), and risk (standard deviation) calculated using Eqs. 1 and 2, respectively (see text for discussion). Coefficient of variation (CV) = SD/$E(U)$.

Acknowledgements

In Illinois, we thank Jeff Kindhart and Anthony Bratsch (University of Illinois Extension) and Robert Fournie who established plots and aided in harvest and analysis. In Minnesota, we thank Sandy Bird, Kelley Dingmann, Katie Gore, Becky Hines, Brady Lenzen, Patrick O'Rourke, and Rebecca Radintz for assistance in the field. This research was supported in part by grants from the Midwest Food Processors Association, Agricultural Utilization Research Institute (Minn.), Novartis Seeds, and the Illinois Council for Food and Agricultural Research (C-FAR).

References

Armstrong, C.L., Parker, G.B., Pershing, J.C., Brown, S.M., Sanders, P.R., Duncan, D.R., Stone, T., Dean, D.A., DeBoer, D.L., Hart, J., Howe, A.R., Morrish, F.M., Pajeau, M.E., Petersen, W.L., Reich, B.J., Rodriquez, R., Santino, C.G., Sato, S.J., Schuler, W., Sims, S.R., Stehling, S., Tarochione, L.J., Fromm, M.E., 1995. Field evaluation of European corn borer control in progeny of 173 transgenic corn events expressing an insecticidal protein from *Bacillus thuringiensis*. Crop Sci. 35, 550–557.

Bartels, D.W., Hutchison, W.D., 1995. On-farm efficacy of aerially applied *Bacillus thuringiensis* for European corn borer (Lepidoptera: Pyralidae) and corn earworm (Lepidoptera: Noctuidae) control in sweet corn. J. Econ. Entomol. 88, 380–386.

Bartels, D.W., Hutchison, W.D., Fritz, V.A., Klacan, G.R., 1995. Effect of *Bacillus thuringiensis* application interval on European corn borer (Lepidoptera: Pyralidae) control in sweet corn. J. Entomol. Sci. 30, 374–389.

Burkness, E.C., Hutchison, W.D., Bolin, P.C., Bartels, D.W., Warnock, D.F., Davis, D.W., 2001. Field efficacy of sweet corn hybrids expressing a *Bacillus thuringiensis* toxin for management of *Ostrinia nubilalis* (Lepidoptera: Crambidae) and *Helicoverpa zea* (Lepidoptera: Noctuidae). J. Econ. Entomol. 94, 197–203.

Carlson, G.A., 1970. A decision theoretic approach to crop disease prediction and control. Am. J. Agr. Econ. 52, 216–223.

Conover, W.J., Iman, R.L., 1981. Rank transformations as a bridge between parametric and nonparametric statistics. The Am. Statist. 35, 124–129.

Flood, B., Foster, R., Hutchison, B., 1995. Sweet corn. In: Foster, R., Flood, B. (Eds.), Vegetable Insect Management: With Emphasis on the Midwest. Meister Publishing, Willoughby, OH, pp. 19–40.

Lynch, R.E., Wiseman, B.R., Plaisted, D., Warnick, D., 1999a. Evaluation of transgenic sweet corn hybrids expressing CryIA(b) toxin for resistance to corn earworm and fall armyworm (Lepidoptera: Noctuidae). J. Econ. Entomol. 92, 246–252.

Lynch, R.E., Wiseman, B.R., Sumner, H.R., Plaisted, D., Warnick, D., 1999b. Management of corn earworm and fall armyworm (Lepidoptera: Noctuidae) injury on a sweet corn hybrid expressing a *cryIA(b)* gene. J. Econ. Entomol. 92, 1217–1222.

Moffitt, L.J., Tanigoshi, L.K., Baritelle, J.L., 1983. Incorporating risk in comparisons of alternative pest control methods. Environ. Entomol. 12, 1003–1011.

Ostlie, K.R., Hutchison, W.D., Hellmich, R.L. (Eds.), 1997. Bt corn and European corn borer: long-term success through resistance management. NCR Public. 602. University of Minnesota, St. Paul, MN.

Rinkleff, J.H., Hutchison, W.D., Campbell, C.D., Bolin, P.C., Bartels, D.W., 1995. Insecticide toxicity in European corn borer (Lepidoptera: Pyralidae): ovicidal activity and residual mortality to neonates. J. Econ. Entomol. 88, 246–253.

SAS Institute, 1995. *SAS/STAT User's Guide*, Version 6. 4th ed. SAS Institute Inc., Cary, NC.

Shim, J.K., Siegel, J.G. and Simon, A.J., 1986. Making use of quantitative decision making. In: The Vest-Pocket MBA, Prentice Hall Inc., Englewood Cliffs, NJ (Chapter 8).