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EVALUATION OF TRANSGENIC CORN (*Zea mays* L.)
RESISTANT TO BOTH GLYPHOSATE AND WESTERN
CORN ROOTWORM (*Diabrotica virgifera virgifera* LeConte)
IN MICHIGAN

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KATHRIN SCHIRMACHER

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By

Kathrin Schirmacher

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ABSTRACT

EVALUATION OF TRANSGENIC CORN (*Zea mays* L.) RESISTANT TO BOTH GLYPHOSATE AND WESTERN CORN ROOTWORM (*Diabrotica virgifera virgifera* LeConte) IN MICHIGAN

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Annual weeds and western corn rootworm (*Diabrotica virgifera virgifera* LeConte) (WCR) can limit corn (*Zea mays* L.) grain yield. With the failure of a corn and soybean [*Glycine max* (L.) Merr.] rotation as an effective control program for WCR, growers are relying more heavily on conventional insecticides to control WCR. Glyphosate has been used as a postemergence (POST) weed control program since the introduction of glyphosate-resistant corn hybrids in 1998. The adoption of glyphosate-resistant corn has increased. The glyphosate-resistant trait is often stacked with other resistance traits. The use of herbicide and insect resistance traits gives producers new options in pest control program. Many studies have looked at the agronomic and economic considerations of using either using insect or herbicide resistance traits in corn hybrids. However, no study has been conducted on corn hybrids containing resistance traits to both herbicides and insects. The objective of this study was to determine the consistency of conventional programs and programs using transgenic corn for control of WCR and annual weeds and to examine the profitability of these programs under a range of Michigan conditions. Field studies were conducted in 2004, 2005, and 2006 at four locations in Mid-Michigan. Sites were selected to reflect a range of annual weed and WCR densities. Treatments consisted of conventional weed management and a management program using glyphosate-resistant corn in combinations with WCR

management programs. Good weed control resulted in increased corn yields at all locations all years. Good weed control was obtained with both glyphosate-based and conventional herbicide programs. Under low WCR densities, the use of any of the WCR control programs tested increased corn yields in one of six environments. Under high WCR densities, the use of the transgenic Bt corn hybrid resulted in increased corn yields in three of six environments compared to no WCR control. In those years where WCR damage was high, all control programs resulted in corn yields greater than when left untreated, with the transgenic *Bt* corn hybrid consistently providing the greatest corn yields. Weed control costs were economically justified under both low and high weed densities, based on gross margins over weed control costs. Gains in gross margins relative to no weed control were reported for all weed control strategies at all locations all years. The presence and intensity of WCR larvae feeding on corn roots varied by year and was less predictable than weed density. The overall gross margin of the no WCR control program at the low WCR sites was often higher than the gross margins of the WCR programs. This indicated that, unlike weed control, the costs associated with the control of WCR in many instances was not justified. At the high WCR sites, the cost of WCR control via either *Bt*-corn or conventional seed or soil insecticide treatment was justified in two of six environments. In those two environments, the *Bt*-hybrid consistently had the highest gross margin gains relative to no WCR control. The adoption of stacked transgenic corn hybrids will likely be related to economic return associated with the control of weeds and WCR. Since gross margins were positively correlated with corn yield ($r^2 = 0.98$), growers should focus on yield potential by choosing high yielding hybrids adapted to local growing conditions.

Für meine liebe Mutter

Marianne Schirmacher
Geb. Schneider

1952-2005

Wir wollen nicht trauern,
dass wir sie verloren haben,
sondern wir wollen uns freuen,
dass wir sie gehabt haben und noch haben,
denn wer im Herrn stirbt,
der bleibt in der Familie

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I would also like to thank past and present graduate students and post-docs in the weed science program. I especially wanted to acknowledge Dr. Aaron Franssen, Ann McCordick, Dr. David Hillger, and Dr. Christy Sprague for their friendship, words of encouragement, and many laughs.

The biggest credit for finishing this degree goes to my family. My parents have always told me to not forget where I came from – the farm. They have instilled in me a love for the land as well as good values, for this I am thankful.

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CHAPTER I

Agronomic Evaluation of Transgenic Corn (*Zea mays* L.) Resistant to Both Glyphosate and Western Corn Rootworm (*Diabrotica virgifera virgifera* LeConte) in Michigan

ABSTRACT

Stacked insect resistant and herbicide resistant traits in field corn are becoming more common in the marketplace. Major in-field stresses affecting Michigan corn yields include competition from annual weeds and western corn rootworm feeding damage. This three-year study examines the consistency of conventional herbicide and insecticide programs and *Bt*-corn/glyphosate-based programs for control of insects and weeds under a range of Michigan conditions. Good weed control increased corn yields at all locations all years. Good weed control was obtained with both glyphosate-based and traditional herbicide programs. Under low western corn rootworm (WCR) densities, the use of control methods increased corn yields in one of six environments. Under high WCR densities, the use of control programs increased corn yields in three of six environments. In those years where WCR damage was high, all control programs provided corn yields higher than when left untreated, with the *Bt*-hybrid consistently providing the greatest yields. Under high WCR damage at Westphalia in 2005 and 2006, the WCR control programs in order of most to least consistent were: the *Bt*-hybrid, soil-applied insecticide (SAI) + low seed treatment (LST), SAI, and high seed treatment (HST). WCR density, rather than the weed density, is likely to be one of the important factors in the adoption of these stacked trait corn hybrids.

Nomenclature: atrazine; glyphosate; mesotrione; s-metolachlor; clothianidin; tefluthrin; European corn borer, *Ostrinia nubilalis* Hübner; western corn rootworm, *Diabrotica virgifera virgifera* LeConte; corn, *Zea mays* L. 'DKC46-24', 'DKC46-28', 'DKC46-22', 'DKC47-10'.

Key Words: insect resistance, herbicide resistance, multiple resistance traits, stacked traits, transgenic, western corn rootworm, corn, yield.

Abbreviations: PRE, preemergence; POST, postemergence; fb., followed by; RR, glyphosate resistant; WCR, western corn rootworm; ECB, European corn borer; *Bt*, *Bacillus thuringiensis*; HST, high seed treatment; LST, low seed treatment; SAI, soil-applied insecticide.

INTRODUCTION

Inter-specific gene transfer technology has led to the development of traits that provide crops with herbicide and insect resistance. The use of herbicide and insect resistant traits gives producers new options in crop protection and broadens the options in pest control programs. Seed companies are now stacking more than one trait into a single corn hybrid, leading to corn hybrids that contain resistance for both herbicides and insects. The trend of increased numbers of stacked transgenic traits marketed by seed companies, and bundled with pesticides sales as a package, will likely continue in the foreseeable future.

A pest that can limit corn grain yield is western corn rootworm (*Diabrotica virgifera virgifera* LeConte) (WCR). With its widespread range and abundance in North America (Krysan and Branson 1983), the WCR is one of the most economically important pests of corn (*Zea mays* L.) (Levine and Oloumi-Sadeghi 1991). Both the larval and adult stage of the WCR damages corn. The larvae injure corn plants by feeding on root tissue, interfering with normal root functions such as nutrient and water absorption, and plant anchorage (Levine and Oloumi-Sadeghi 1991). In the case of strong winds and rainstorms, plant lodging may occur resulting in yield losses as well as harvesting difficulties. The adults interfere with the reproductive success of the plants by damaging silks and tassels, resulting in poor ear development. The estimated cost of control and yield losses associated with corn rootworms in corn is roughly $1 billion annually in the US (Gray 2000; Metcalf 1986). The insect can adapt to cultural practices, increasing the risk of economic losses. In the Midwest, a corn-soybean [*Glycine max* (L.) Merr.)] crop rotation was for a long time the recommended program to prevent root injury caused by the WCR. WCR oviposition occurs primarily in corn fields and larvae must feed on corn roots the following spring to complete their life cycle (Levine and Oloumi-Sadeghi 1991). Long-term use of this rotational system selected for a variant strain of the WCR capable of laying eggs not only in corn but also in soybean, oats (*Avena sativa* L.), and alfalfa (*Medicago sativa* L.) circumventing crop rotation as a management tool (Levine et al. 2002; Rondon and Gray 2003, 2004). Since the failure of a corn-soybean rotation as an effective control program growers have had to rely on soil-applied insecticides and corn kernels treated with insecticides to control WCR (Levine and Oloumi-Sadeghi 1991). Corn producing insecticidal toxins from *Bacillus thuringiensis* (*Bt*) has the potential of simplifying WCR management. The genes allowing for the expression of Cry3Bb1 (Monsanto), Cry34Ab1/Cry35Ab1 (Dow AgroSciences), and Cry3A (Syngenta) proteins were inserted into corn thus conferring host-plant resistance. This allows for the control of corn rootworm without the application of broad-spectrum insecticides (Vaughn et al. 2005).

Weeds interfering with corn can affect the quality and quantity of marketable product. Summer annual weed species are usually problematic in summer annual crops such as corn and soybean (Davis et al. 2005). For example, common lambsquarters (*Chenopodium album* L.) when left untreated caused corn yield loss as high as 58% (Sibuga and Bandeen 1980). A maximum yield loss of 12% was recorded by Beckett et al. (1988) at a density of 4.9 common lambsquarters plants per m of corn row. Another troublesome weed in row crops in the Midwestern states is velvetleaf (*Abutilon theophrasti* Medic.) (Bello et al. 1995; Stubbendieck 1995). Lindquist et al. (1996) reported corn yield losses of 15-20% in Michigan with velvetleaf at a density of 10 plants per m. Giant foxtail (*Setaria faberi* Herrm.) and other foxtail spp. were considered by Fausey et al. (1997) to be some of the most problematic and widespread annual grass weeds in Midwestern row crop production. In Michigan, 10 giant foxtail plants per m of row reduced corn yields by 14% through season-long competition (Fausey et al. 1997).

Glyphosate [*N*-(phosphonomethyl)glycine] is a non-selective herbicide that was initially used to control vegetation in non-cropland areas (Carlson and Burnside 1984; Wilson et al. 1985). Corn hybrids resistant to the herbicide glyphosate have been used as an alternative option for post-emergence weed control programs since 1998 (Duke 2005). The adoption rate of glyphosate-resistant corn, although lower than that of glyphosate-resistant soybean, has increased over the last several years (Dill 2005). In the US, glyphosate was applied to 31 % of planted corn acres in 2005, a 12 % increase in glyphosate usage from 2003 (USDA-NASS 2004, 2006). Furthermore, glyphosate-resistance is often stacked with other resistance traits. Previous research on glyphosate-resistant crops dealt with the effectiveness of weed control (Tharp and Kells 2002; Zuver et al. 2006) and application timing (Dalley et al. 2004; Gower et al. 2003) as opposed to the integration with other pest control programs.

Many studies have looked at either insect resistance or herbicide resistance traits. To date, a single study conducted in cotton (*Gossypium hirsutum* L.) documented the stability of cotton yield among conventional and *Bt*/glyphosate-resistant cultivars (Blanche et al. 2006). No such study has been conducted on corn hybrids containing multiple-resistance traits. As with any new insect or weed management technology, management programs must be evaluated as part of an integrated system. Thus, the objective of our study was to determine the consistency of conventional herbicide and insecticide programs and programs using transgenic corn for control of WCR and annual weeds under a range of Michigan conditions.

MATERIALS AND METHODS

Experimental Description. Field experiments were conducted in 2004, 2005 and 2006, at four locations each year. These were two separate sites on the Crop and Soil Sciences Research Farm at Michigan State University (MSU) in East Lansing and two off-campus sites on commercial farms within 50 km of the MSU campus (Table 1). Sites were selected to reflect a range of weed density and WCR densities experienced by MI producers. Experimental sites were chosen based on past history of pest infestation. High WCR density sites had a history of damage in corn planted after corn. Low WCR density sites were planted to corn in fields annually rotated between corn and soybean.

Near-isogenic corn hybrids[1] were used throughout the experiment to minimize agronomic differences. In 2004, two corn hybrids were used: 1) 'DKC46-28' with glyphosate resistance (RR) and 2) 'DKC46-24' with resistance to corn rootworm in addition to RR (WCR/RR). In 2005, a three-way stacked hybrid with resistance to European corn borer (*Ostrinia nubilalis* Hübner) (ECB), WCR, RR was approved for commercial production in the US. Thus, in 2005 and 2006, we used isogenic hybrid lines with RR/ECB ('DKC47-10') and WCR/RR/ECB ('DKC46-24') to minimize experimental error attributable to ECB. Corn hybrids with the rootworm resistance traits ('DKC46-24' and 'DKC46-22') were available commercially only with a seed treatment of clothianidin[2] at a low dose (0.25 mg a.i./kernel) (LST) to control soil insects at planting. 'DKC46-28' and 'DKC47-10' were commercially available untreated or with a low or high (1.25 mg a.i./kernel) (HST) dose of clothianidin.

All corn hybrids were planted in rows 0.76 m apart at a seeding rate of 74,000 seed/ha. Plots were four rows wide by 10.7 m long. The experimental design was a randomized complete block with four replications and 22 treatments (Table 2). Treatments consisted of combinations of conventional insecticide and herbicide programs and *Bt*-corn/glyphosate-based weed and WCR management programs. Appropriate controls were included in the design of the experiment and consisted of combinations of weed (no weed control; weed free) and WCR (untreated; low dose of clothianidin [0.25 mg a.i/kernel]; *Bt*-hybrid expressing Cry3Bb1) control programs. The control program with the low dose of clothianidin seed treatment was included because the *Bt*-hybrid was commercially only available with a low dose of the clothianidin seed treatment.

Weed Control and Evaluations. A weed control program based on glyphosate resistant corn using postemergence (POST) applications of glyphosate[3] and a conventional weed control program using selected herbicides to control weed species present were used throughout the study. Glyphosate-based weed management programs included (1) a preemergence (PRE) herbicide application of atrazine (0.91 kg ai/ha) plus S-metolachlor[4] (0.71 kg ai/ha) followed by a POST herbicide application of glyphosate (0.87 kg/ha), and (2) two separate POST herbicide applications of glyphosate (0.87 kg/ha each). All glyphosate applications included 2% (w/w) ammonium sulfate. Conventional weed management programs included (1) a PRE herbicide application of mesotrione (0.19 kg ai/ha) plus S-metolachlor (1.88 kg ai/ha) plus atrazine[5] (0.70 kg ai/ha), and (2) a PRE herbicide application of S-metolachlor[6] (1.39 kg ai/ha) followed by a POST herbicide application (determined by scouting for weed species and density). Herbicide treatments were applied with a tractor mounted, compressed-air sprayer calibrated to deliver 187 L/ha at 207 kPa through 8003 flat fan nozzles[7]. Predominant annual broadleaf and grass weed species were counted by species prior to the first POST herbicide application (except for plots treated with PRE herbicides). At physiological maturity, all weed species in two permanent quadrats (0.76 x 1 m) placed within the center two rows of each plot were counted. The above-ground parts of these weeds were harvested, dried for 5 days at 60 C, and weighed.

Corn Rootworm Control and Evaluations. WCR control programs included (1) a hybrid expressing Cry3Bb1 *Bt*, (2) the conventional soil-applied granular insecticide (SAI) tefluthrin[8] applied in-furrow at a rate of 6.16 kg/ha, (3) a combination of the conventional SAI tefluthrin applied in-furrow at a rate of 6.16 kg/ha + a commercially applied seed treatment of clothianidin at a low rate (0.25 mg a.i./kernel) (LST), and (4) a commercially applied seed treatment of clothianidin at a high rate (1.25 mg a.i./kernel) (HST).

Larval injury was evaluated by digging three root masses from each treatment in late-July/early-August of each year. All roots were taken from the outer two rows of each plot (i.e. non-yield rows). Root masses were soaked then cleaned with a power washer. Injury was visually assessed using the Iowa State University Node-Injury Scale (Oleson et al. 2005; Nowatzki et al. 2002), described as 0.0 = no feeding damage; 1.0 = one node or the equivalent of an entire node, eaten back to within approximately 5 cm of the stalk; 2.0 = two nodes eaten; and 3.0 = three or more nodes eaten. Additionally, a score of 0.01 stood for only light scarring/ or channeling (shallow grooves on the outside of a root), score of 0.10 represented one pruned root, and two to three pruned roots represented a node-injury score of 0.25.

Corn stand and yield. Stand counts were taken in the middle two rows of each plot after crop emergence to ensure uniformity of corn density across a trial. The middle two rows of each plot were harvested with a plot combine at maturity. Corn grain yields were adjusted to 15.5% moisture.

Data Analysis

Weed Control. To illustrate the level and consistency of weed control, weed densities and weed biomass data are presented using boxplot figures. Boxplots are an indicator of consistency (Ott and Longnecker 2001). In each boxplot, the box represents 50 % of the observations and the line outside the boxes represents 90 % of the observations. Shorter boxes and lines indicate greater consistency among observations. The thicker-horizontal black bar across each boxplot indicates the mean of the observations and the thinner-horizontal back bar indicates the median of the observations.

Root damage. Levels of damage were different across years at all sites ($p < 0.0001$ for all sites) and sites by years are described separately. Root data were log transformed for statistical analysis and back-transformed for data presentation. Data were analyzed by year using the PROC MIXED function in SAS (SAS Institute 2007) and the differences in treatments were separated by comparing the differences of Least Square Means ($\alpha = 0.05$).

Corn Yield. By eliminating the controls, the remaining treatments formed a factorial design. Corn yield potential varied by site and was analyzed separately by location and by year. There were no interactions among herbicide and insecticide treatments on corn yield at any of the sites. However, both factors were themselves key in affecting corn yields as they related to pest density levels. Corn yield data were subjected to analysis of variance using PROC GLM function in SAS (SAS Institute 2007). Weed and WCR treatments means were separated using Fisher's Protected LSD test ($\alpha = 0.05$).

RESULTS AND DISCUSSION

Weed Control. As expected, weed densities at the MSU2 and Mason/Eaton Rapids sites were high, ranging from 138 to 819 weeds per m^2 prior to POST herbicide application (Table 3). The field locations at MSU1 and Westphalia were selected prior to planting to have low weed densites. As expected, weed density was low at these locations, ranging from 4 to 24 weeds per m^2 prior to POST herbicide application (Table 3). The dominant weeds present at the high weed density sites were annual grasses which consisted mostly of giant foxtail and common lambsquarters. Only at MSU2 was common ragweed (*Ambrosia artemisiifolia* L.) present in high numbers. The MSU2 trial was located in the same field site in 2004 and 2006 and in an adjacent field in 2005. MSU1, Westphalia, and Mason/Eaton Rapids trials were located in different fields every year.

Low weed density locations. At MSU1, at the end of the growing season, plots receiving conventional herbicides had lower weed densities than the plots receiving glyphosate (Figure 1). The higher weed densities in the plots receiving glyphosate did not result into higher weed biomass (Figure 2), indicating that most weeds present were small. At Westphalia, mean weed density values were similar for all plots with herbicide applications (Figure 1). At Westphalia, the highest and most variable weed biomass mean value was for weeds collected in the conventional PRE herbicide program plots (Figure 2). At both sites, the use of herbicides decreased the total number of weeds and weed biomass relative to no weed control (Figures 1 and 2).

High weed density locations. At MSU2, the conventional PRE fb. POST herbicide application program resulted in the lowest weed density plots, while the remaining programs resulted in higher, more variable densities (Figure 1). There were no distinct trends in weed densities when comparing the glyphosate-based versus conventional weed control programs plots and single-pass versus sequential herbicide programs plots at MSU2. At Mason/Eaton Rapids, plots receiving either the PRE fb. POST herbicide applications in the conventional and glyphosate-based weed control programs had the least variable and lowest weed densities. The conventional PRE herbicide program resulted in the highest and most variable weed density mean (Figure 1). At both sites, all herbicide programs decreased the total number of weeds relative to no weed control (Figure 1).

High weed densities did not translate into high weed biomass (Figure 2), indicating that most weeds present were small. At both MSU2 and Mason/Eaton Rapids sites, the conventional PRE herbicide application resulted in the greatest and most variable weed biomass (Figure 2). PRE herbicide applications allow for critical early season weed control. The residual activity of these products is highly dependent on moisture after application to activate the herbicide and to provide adequate, season-long weed control (Rabaey and Harvey 1997; Spandl et al. 1997). Tharp and Kells (2002) recommended the use of residual herbicide combinations with POST herbicide applications to increase season-long weed control.

Corn Rootworm Control. The field locations at Westphalia and Mason/Eaton Rapids were selected prior to planting for high WCR densities. Unlike weed density, WCR density was more difficult to predict from year to year. Based on root damage and number of WCR adults at the research sites, WCR density was high at Westphalia in 2005 and 2006 and at Mason/Eaton Rapids in 2006. However, the WCR density ranged from low at Westphalia in 2004 and Mason/Eaton Rapids in 2005 to moderate at Mason/Eaton Rapids in 2004. The field locations at MSU1 and were selected prior to planting to have low WCR density. WCR density was low in most years but increased to moderate levels at MSU2 in 2006.

Low WCR density locations. At MSU1, root damage was low in all three years of the study (Figure 3). At MSU2, overall root damage was low (0.01) in 2004 and 2005 (Figure 3). A score of 0.01 indicates very light scarring and denotes that the root system is not perfect (i.e. score = 0). Despite differences in treatment mean values at both sites, the low amount of damage was expected in a corn-soybean rotation. These differences are not considered to be important due to the overall low amount of damage observed. In 2006 at MSU2, injury level in the untreated control was slightly higher (0.3) than in previous years (Figure 3). A score of 0.3 indicates three pruned roots on the root mass. Oleson et al. (2005) noted that root damage above 0.1 constitutes major root damage. This is an indication that the WCR variant, resistant to a corn-soybean rotation, is present on the MSU campus. In this trial, all corn rootworm control programs protected corn roots with the *Bt*-hybrid, the SAI, and the SAI + LST providing the best protection (Figure 3).

High WCR density locations. At Westphalia, in 2004, heavy rainfall flooded the plot area and delayed planting until early June (Table 1). The previous season, the producer reported heavy WCR damage in the field. However, the plots in 2004 had low damage, even in the untreated control (Figure 3). Hoffman et al. (2000) noted that delaying corn planting was an effective cultural control method against WCR root feeding. The co-occurrence of a very susceptible corn growth phase and a peak rootworm larval population is prevented by delaying corn planting (Carlson and Gauge 1989). At the same site in 2005 and 2006 there was considerable larval feeding (1.00 to 1.25) on corn roots that had no protection. A score of 1.00 indicates that one entire root node has been pruned off of the root mass. Under high WCR conditions, both the *Bt*-hybrid and the conventional insecticide treatments protected corn roots from feeding, with the *Bt*-hybrid having the least amount of damage on roots (Figure 3).

At Mason/Eaton Rapids, we anticipated high WCR densities based on prior corn-corn rotation, but observed low overall root damage in 2004 and 2005 (Figure 3). In 2004, delayed planting is the likely cause of low root damage (Hoffman et al. 2000). The field site only had two years of corn prior to the establishment of the trial which may not have been sufficient for the buildup of WCR larval densities capable of producing a significant amount of damage to corn roots. Considerably higher root damage was observed in 2006, and results were similar to those at Westphalia. In 2006, all WCR treatments protected corn roots with the *Bt*-hybrid having the lowest amount of damage (Figure 3). At both of these sites, in those years where WCR densities were high, there were no differences in the amount of feeding between the LST and no insecticide controls (Figure 3). This indicates that under high corn rootworm levels the LST rate would not be sufficient to protect corn roots from damage. This is similar to Steffey et al. (2005) who described that the performance of seed applied insecticide treatments to be inconsistent under conditions of high WCR density and that these products do not perform as well in protecting corn roots from injury as most SAI.

Corn Yield.

Low weed density locations. At MSU1, there were no differences in corn yield among herbicide treatments in 2004 and 2005 (Table 5). In 2006, the corn yield obtained was highest with the glyphosate-based PRE fb. POST and lowest with the conventional PRE herbicide programs (Table 5). The corn yield with the conventional PRE herbicide program did not differ from the glyphosate-based POST fb. POST or conventional PRE fb. POST herbicide programs. At Westphalia, there were no differences in corn yield among herbicide programs in 2005 and 2006 (Table 5). In 2004, the conventional PRE herbicide program resulted in the highest corn yield and the conventional PRE fb. POST herbicide program the lowest (Table 5). In most years, a single PRE herbicide application may be sufficient to control weeds under low weed density. However, lack of rainfall after PRE herbicide application may result in inadequate herbicide incorporation and incomplete weed control. Similarly, a lack of weed control may occur in the case of excess precipitation. The herbicide is activated but may be leached beyond the weed seed germination zone (Walker and Roberts 1975). In both instances, a POST herbicide application may be necessary to adequately control weeds. Under low weed density, the glyphosate-based PRE fb. POST and POST fb. POST herbicide programs resulted in corn yields not significantly different from the highest in six of six environments (Table 5). Corn yields obtained with the conventional PRE and PRE fb. POST herbicide programs were not different than the highest corn yields in five of six environments (Table 5).

High weed density locations. At MSU2 there were differences in corn yield among herbicide treatments in 2004 and 2005, but there were no consistent trends across years (Table 5). In 2004, the glyphosate-based PRE fb. POST herbicide program resulted in the highest corn yield (Table 5). There were no differences among herbicide programs for corn yield at MSU2 in 2006 (Table 5). In 2004 and 2005 at Mason/Eaton Rapids, there were no differences in corn yields among treatments. In 2006, the lowest corn yields were obtained with the conventional PRE herbicide program. Corn receiving the glyphosate-based PRE fb. POST herbicide program had yields similar to the highest yields obtained in six of six environments. The conventional PRE fb. POST herbicide program resulted in corn yields similar to the highest in five of six environments. Corn receiving the glyphosate-based POST fb. POST herbicide program had yields equal to the highest in four of six environments while corn that received the conventional PRE herbicide program had yields similar to the highest in only three of six environments (Table 5). The PRE fb. POST herbicide programs, regardless of whether the treatment was glyphosate-based or conventional, most consistently resulted in high corn yields.

Low WCR density locations. In 2004, there were no differences in corn yield among WCR control programs at both the MSU1 and MSU2 locations (Table 6). These results indicate what would be anticipated under low WCR density. In 2005, the corn variety

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receiving the high dose of clothianidin seed treatment had the lowest corn yields at all locations (Table 6). This treatment, resulted in a significant reduction in corn population at all locations in 2005 (Table 7). The lower corn yields were attributable to this reduced population, which is likely related to the seed treatment process. In 2006, the *Bt* corn hybrid had the highest and the SAI had the lowest corn yields at both low WCR density locations (Table 6).

We saw an increase in overall damage to corn roots (Figure 1) and an increasing effect of WCR on corn yield at MSU2 over the course of this three-year study (Table 6). The MSU2 location was planted to corn after soybean to minimize WCR damage. This increased level of feeding, as well as the increased density of WCR adults observed in soybean on campus, indicates the presence of the WCR variant in central MI. In summary, at the low WCR density sites, the *Bt*-hybrid had corn yields not different from the highest in six of six environments. From both the conventional SAI and SAI + LST programs corn yields were observed to be similar to the highest yielding treatments in four of six environments. Corn receiving the HST treatment yields similar to the highest in three of six environments. The variable corn yields with the HST was due to the loss in corn population in 2005 (Table 7).

High WCR density locations. In 2004, there were no differences in corn yield observed among WCR control programs at either the Westphalia or Mason/Eaton Rapids locations, which is not the expected results at a high WCR density site. Both sites were anticipated to have a high density of WCR, however neither did. Rainfall three times above the monthly average (Table 4) in the Mid-Michigan area may have played a role in the lack of WCR injury observed at Westphalia. Excess precipitation could have compromised our anticipated high WCR density levels at Westphalia via larval drowning during the 2004 growing season. Planting at both high WCR density sites was delayed in 2004 (Table 1) and, as noted previously, delaying planting allows for the avoidance of peak larval populations with the corn crop (Hoffman et al. 2000). In 2006, there were no differences in corn yields observed among the various WCR control programs at Mason/Eaton Rapids (Table 6). However, at Westphalia in 2006, there were differences among treatments with the *Bt*-hybrid having the highest corn yield (Table 6). There was no reduction in corn population associated with the HST at Westphalia in 2006, however this treatment still resulted in corn yields lower than all other control programs (Table 6). In summary, at the high WCR sites, the *Bt*-hybrid had corn yields similar to the highest in six of six environments. The corn receiving SAI, SAI + LST, and HST had yields similar to the highest corn yields in four, five, and three environments, respectively. Overall, the *Bt*-hybrid was the most effective and consistent system at protecting corn yield under high WCR density levels.

The presence of weeds had a considerable effect on corn yields at all locations, including all low weed density sites (Table 8). At the low weed density sites, corn yield losses associated with weeds ranged from 30 to 77 % and 22 to 48 % at MSU1 and Westphalia, respectively (Table 8). The effect of weeds on corn yield at MSU2 was 76 %, 89 %, and 95 % in 2004, 2005 and 2006, respectively (Table 8). The effect of weeds on corn yield at Mason/Eaton Rapids was 36 %, 42 %, and 77 % in 2004, 2005, and 2006, respectively (Table 8). Corn yields were greatly increased with any weed control program compared with uncontrolled weeds (Tables 5 and 8).

WCR reduced corn yield less than 6% in five of six environments at the low WCR density locations. In 2006 at MSU2, corn yield loss associated with WCR was 12 %, a noted increase from past years. At Westphalia, corn yield losses attributable to WCR were 31% to 38% in 2005 and 2006, respectively. The *Bt*-hybrid had the greatest corn yields at Westphalia in 2005 and 2006, however the conventional WCR control programs still provided greater corn yields than no insect control (Table 6 and 8). Overall corn yield loss associated with WCR at Mason/Eaton Rapids was low in 2004 and 2005 but reached nearly 23 % in 2006. At these anticipated high WCR density locations, control of WCR significantly increased corn yields in three of six environments. If the expected larval densities had not been compromised in 2004, WCR control at these high WCR density locations may have increased corn yields at these two locations as well. When compared to weed control, the effect of WCR on corn yield was more variable in that WCR control did not increase corn yield at each site and each year.

These results indicate that excellent weed control can be obtained in corn with either glyphosate-based or with conventional herbicide programs. Control of annual weeds is essential in preserving corn yields, even in low weed density sites. Regardless of weed density, weed control was necessary at all sites in all years to avoid significant corn yield loss from weeds. WCR control increased corn yields in one of six environments at the low and three of six environments at the high WCR density locations. The results from this field research indicate that the presence and larval density of WCR should be an important factor for Michigan growers to consider regarding the decision to adopt these stacked transgenic corn hybrids. However, the main consideration for the adoption of these new pest management technologies will likely be the cost of control and the economic return associated with the control of weeds and WCR.

Source of Materials

[1] Dekalb Genetics Corp., Monsanto Company, St. Louis, MO 63167

[2] Poncho 600, Bayer CropScience, Research Triangle Park, NC 27709

[3] Roundup WeatherMax, Monsanto Company, St. Louis, MO 63167

[4] Bicep II Magnum, Syngenta Crop Protection, Inc. Greensboro, NC 27409

[5] Lumax, Syngenta Crop Protection, Inc. Greensboro, NC 27409

[6] Dual II Magnum, Syngenta Crop Protection, Inc. Greensboro, NC 27409

[7] TeeJet Spraying Systems Co., Wheaton, IL 60188

[8] Force 3G, Syngenta Crop Protection, Inc. Greensboro, NC 27409

[9] SAS Institute Inc., Cary, NC 27513

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Table 1. Anticipated weed and corn rootworm (WCR) density levels, soil characteristics, and planting dates at each location in 2004, 2005, and 2006.

Site	Year	Location	Annual weed density†	WCR density†	Soil texture	Soil pH	Soil OM	Planting date
1	2004				Clay Loam	7.4	2.3	April 30
	2005	MSU	LOW	LOW	Sandy Loam	6.5	1.1	May 4
	2006				Sandy loam	6.6	1.0	April 29
2	2004				Clay Loam	7	3	May 17
	2005	MSU2	HIGH	LOW	Clay Loam	6.7	2.6	May 5
	2006				Clay Loam	6.6	2.4	May 4
3	2004				Sandy Loam	5.8	2.2	June 4
	2005	Westphalia	LOW	HIGH	Clay Loam	7	2.4	May 4
	2006				Loam	7.5	2.6	April 29
4	2004	Mason			Sandy loam	6.7	2.9	June 4
	2005	Eaton Rapids	HIGH	HIGH	Loam	6.3	3	May 4
	2006	Mason			Sandy Loam	7.1	2.6	April 29

† Anticipated pest densities based on field history.

Table 2. Treatments combining weed and corn rootworm management programs, Michigan (2004-2006).

	Weed control programs		Corn rootworm control programs	
Trt	Type[a]	Description	Type[a]	Description
1	PRE fb. POST (T)	atrazine + s-metolachlor fb. glyphosate	*Bt*-hybrid (T)	Hybrid resistance + clothianidin
2	POST fb. POST (T)	glyphosate fb. glyphosate	*Bt*-hybrid (T)	Hybrid resistance + clothianidin
3	PRE (C)	mesotrione + s-metolachlor + atrazine	*Bt*-hybrid (T)	Hybrid resistance + clothianidin
4	PRE fb. POST (C)	s-metolachlor fb. POST (scouting)	*Bt*-hybrid (T)	Hybrid resistance + clothianidin
5	none	No weed control	*Bt*-hybrid (T)	Hybrid resistance + clothianidin
6	none	Weed free	*Bt*-hybrid (T)	Hybrid resistance + clothianidin
7	PRE fb. POST (T)	atrazine + s-metolachlor fb. glyphosate	SAI[†] (C)	tefluthrin
8	PRE fb. POST (T)	atrazine + s-metolachlor fb. glyphosate	SAI + LST[†] (C)	tefluthrin + clothianidin
9	PRE fb. POST (T)	atrazine + s-metolachlor fb. glyphosate	HST[†] (C)	clothianidin
10	POST fb. POST (T)	glyphosate fb. glyphosate	SAI (C)	tefluthrin
11	POST fb. POST (T)	glyphosate fb. glyphosate	SAI + LST (C)	tefluthrin + clothianidin
12	POST fb. POST (T)	glyphosate fb. glyphosate	HST (C)	clothianidin
13	PRE (C)	mesotrione + s-metolachlor + atrazine	SAI (C)	tefluthrin
14	PRE (C)	mesotrione + s-metolachlor + atrazine	SAI + LST (C)	tefluthrin + clothianidin
15	PRE (C)	mesotrione + s-metolachlor + atrazine	HST (C)	clothianidin
16	PRE fb. POST(C)	POST (scouting)	SAI (C)	tefluthrin
17	PRE fb. POST (C)	POST (scouting)	SAI + LST (C)	tefluthrin + clothianidin
18	PRE fb. POST (C)	POST (scouting)	LST (C)	clothianidin
19	none	No weed control	none	No insect control
20	none	No weed control	LST (C)	clothianidin
21	none	Weed free	none	No insect control
22	none	Weed free	LST (C)	clothianidin

[a] Abbreviations: PRE, preemergence; POST, postemergence; fb., followed by; SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic corn program for either weed or insect control; C, denotes a conventional herbicide or insecticide program.

[†] SAI was the soil applied insecticide tefluthrin; LST was a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST was a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

Table 3. Weed densities in a permanently established quadrat at high and low weed density level sites prior to postemergence herbicide application.[a,b]

Location (weed density)	Year	Weed densities (m^2)						
		ABUTH	ANGR	AMBEL	AMARE	CHEAL	POLPY	Total
		weeds/m^2						
MSU1 (low)								
	2004	0	13	10	2	5	0	30
	2005	1	1	5	1	25	1	34
	2006	0	12	4	1	3	0	20
MSU2 (high)								
	2004	2	133	108	16	58	45	362
	2005	35	445	1	16	316	6	819
	2006	14	215	215	22	226	0	692
Westphalia (low)								
	2004	5	2	11	0	2	0	20
	2005	2	1	0	0	1	0	4
	2006	2	2	0	1	1	0	6
Mason/Eaton Rapids (high)								
	2004	4	275	20	3	73	0	375
	2005	0	328	3	3	1	0	335
	2006	25	27	0	32	54	0	138

[a] On average weeds were between 5-10 cm tall at time of first postmergence application.

[b] Abbreviations: ABUTH = velvetleaf; ANGR = annual grasses; AMBEL = common ragweed; AMARE = redroot pigweed; CHEAL = common lambsquarters; POLPY = Pennsylvania smartweed.

Table 4. Monthly precipitation recorded at East Lansing, MI (2004-2006).[a]

Month	2004	2005	2006	Normal[b]
	mm			
May	206	33	111	69
June	89	109	71	89
July	102	116	80	76
August	87	16	92	79
Total[c]	484	274	354	313

[a] Rainfall was recorded at the Michigan State University Department of Horticulture Teaching and Research Center in East Lansing.
[b] Average monthly precipitation measure at East Lansing from 1951 to 1980.
[c] Total rainfall from May 1 to August 31.

Table 5. Corn yield at all locations as influenced by weed control program.

Weed control program[a]	LOW WEED DENSITY					
	MSU1			Westphalia		
	2004	2005	2006	2004	2005	2006
	---kg/ha---					
PRE fb. POST (T)	15,929 a	12,168 a	11,008 a	10,544 ab	9,018 a	10,601 a
POST fb. POST (T)	15,802 a	12,366 a	10,856 ab	10,346 ab	8,578 a	11,018 a
PRE (C)	15,638 a	12,169 a	10,119 b	10,799 a	8,466 a	10,527 a
PRE fb. POST (C)	15,750 a	11,872 a	10,642 ab	9,911 b	8,702 a	10,402 a
LSD (0.05)[b]	875	993	886	776	1,016	1,233
	HIGH WEED DENSITY					
	MSU2			Mason/Eaton Rapids		
	2004	2005	2006	2004	2005	2006
	---kg/ha---					
PRE fb. POST (T)	14,988 a	14,161 a	12,974 a	10,372 a	10,871 a	11,293 a
POST fb. POST (T)	13,933 c	13,649 ab	13,174 a	10,245 a	10,889 a	10,894 a
PRE (C)	14,583 b	13,211 b	12,625 a	10,942 a	10,714 a	7,584 b
PRE fb. POST (C)	14,423 b	13,251 ab	12,482 a	10,632 a	10,556 a	10,495 a
LSD (0.05)[b]	331	933	902	874	1,235	1,456

[a] Abbreviations: PRE, preemergence; POST, postemergence; fb., followed by; T, denotes a transgenic corn program for weed control that is based on the herbicide glyphosate; C, denotes a conventional herbicide program.

[b] Means within a column followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.

Table 6. Corn yield at all locations as influenced by WCR control program.

	LOW WCR DENSITY[a]					
	MSU1			MSU2		
WCR control program[b,c]	2004	2005	2006	2004	2005	2006[†]
	kg/ha					
Bt-hybrid (T)	15,551 a	12,433 a	11,133 a	14,497 a	14,404 a	13,758 a
SAI (C)	15,608 a	12,915 a	10,396 b	14,477 a	14,226 ab	12,381 c
SAI + LST (C)	16,214 a	12,592 a	10,819 ab	14,676 a	13,758 b	13,043 b
HST (C)	15,776 a	10,635 b	10,743 ab	14,277 a	11,883 c	12,960 b
LSD (0.05)[d]	858	762	674	419	644	604

	HIGH WCR DENSITY[a]					
	Westphalia			Mason/Eaton Rapids		
	2004[‡]	2005	2006	2004[†]	2005[‡]	2006
	kg/ha					
Bt-hybrid (T)	10,414 a	10,203 a	11,835 a	10,755 a	11,305 a	10,492 a
SAI (C)	10,343 a	8,332 b	10,645 b	10,309 a	11,135 a	10,373 a
SAI + LST (C)	10,380 a	8,714 b	11,001 ab	10,699 a	10,698 ab	10,084 a
HST (C)	10,462 a	7,516 c	9,314 c	10,412 a	9,891 b	9,929 a
LSD (0.05)[d]	812	741	1,005	884	1,171	1,785

[a] Anticipated WCR density based on past field history.

[b] Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[c] SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[d] Means within a column followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.

[†] Actual WCR density was intermediate.

[‡] Actual WCR density was low.

Table 7. Corn stand density by WCR control program at all locations in 2005.

WCR control program[a,b]	MSU1	MSU2	Westphalia	Mason/Eaton Rapids
	plants/plot row			
Bt-hybrid (T)	55.6 a	53.7 a	53.6 a	56.9 a
SAI (C)	53.7 a	51.0 a	54.0 a	55.6 a
SAI + LST (C)	53.6 a	52.5 a	54.7 a	56.9 a
HST (C)	36.5 b	40.3 b	32.5 b	46.5 b
LSD (0.05)[c]	2.4	3.6	3.1	1.5

[a] Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[b] SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[c] Means within a column followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.

Table 8. Combination of best and worst WCR and weed control programs[a] available to predict corn yield loss.

	LOW WCR + LOW WEED[†]			LOW WCR + HIGH WEED[†]		
	MSU1			MSU2		
WCR + weed control combinations[b]	2004	2005	2006	2004	2005	2006
	kg/ha					
Bt-hybrid + weed free	15,862 a	13,156 a	10,492 a	14,062 a	14,689 a	13,371 a
Bt-hybrid + no weed control	11,064 b	3,041 b	6,494 b	3,414 b	1,682 b	708 c
No WCR control + weed free	15,350 a	13,883 a	9,897 a	14,187 a	14,062 a	11,739 b
Effect of weeds on yield[c]	**30.2 %**	**76.9 %**	**38.1 %**	**75.7 %**	**88.5 %**	**94.7 %**
Effect of WCR on yield[d]	**3.2 %**	--	**5.7 %**	--	**4.3 %**	**12.2 %**
	HIGH WCR + LOW WEED[†]			**HIGH WCR + HIGH WEED[†]**		
	Westphalia			Mason/Eaton Rapids		
	2004	2005	2006	2004	2005	2006
	kg/ha					
Bt-hybrid + weed free	10,797 a	9,730 a	12,116 a	9,917 a	10,832 a	12,755 a
Bt-hybrid + no weed control	8,448 b	5,062 c	9,042 b	6,356 b	6,252 b	2,885 c
No WCR control + weed free	10,672 a	6,780 b	7,470 c	9,507 a	11,371 a	9,875 b
Effect of weeds on yield[c]	**21.8 %**	**48.0 %**	**25.4 %**	**35.9 %**	**42.3 %**	**77.4 %**
Effect of WCR on yield[d]	**1.2 %**	**30.3 %**	**38.3 %**	**4.1 %**	--	**22.6 %**

[a] Yields were taken from the control plots and not the highest yielding treatment. The yield loss incurred from either weed or insects could potentially be higher.

[b] Treatments were separated by comparing the differences of Least Square Means ($\alpha = 0.05$).

[c] Difference between yields from *Bt*-hybrid + weed free and *Bt*-hybrid + no weed control.

[d] Difference between yields from *Bt*-hybrid + weed free and no WCR control + weed free.

[†] Anticipated weed and WCR density based on past field history.

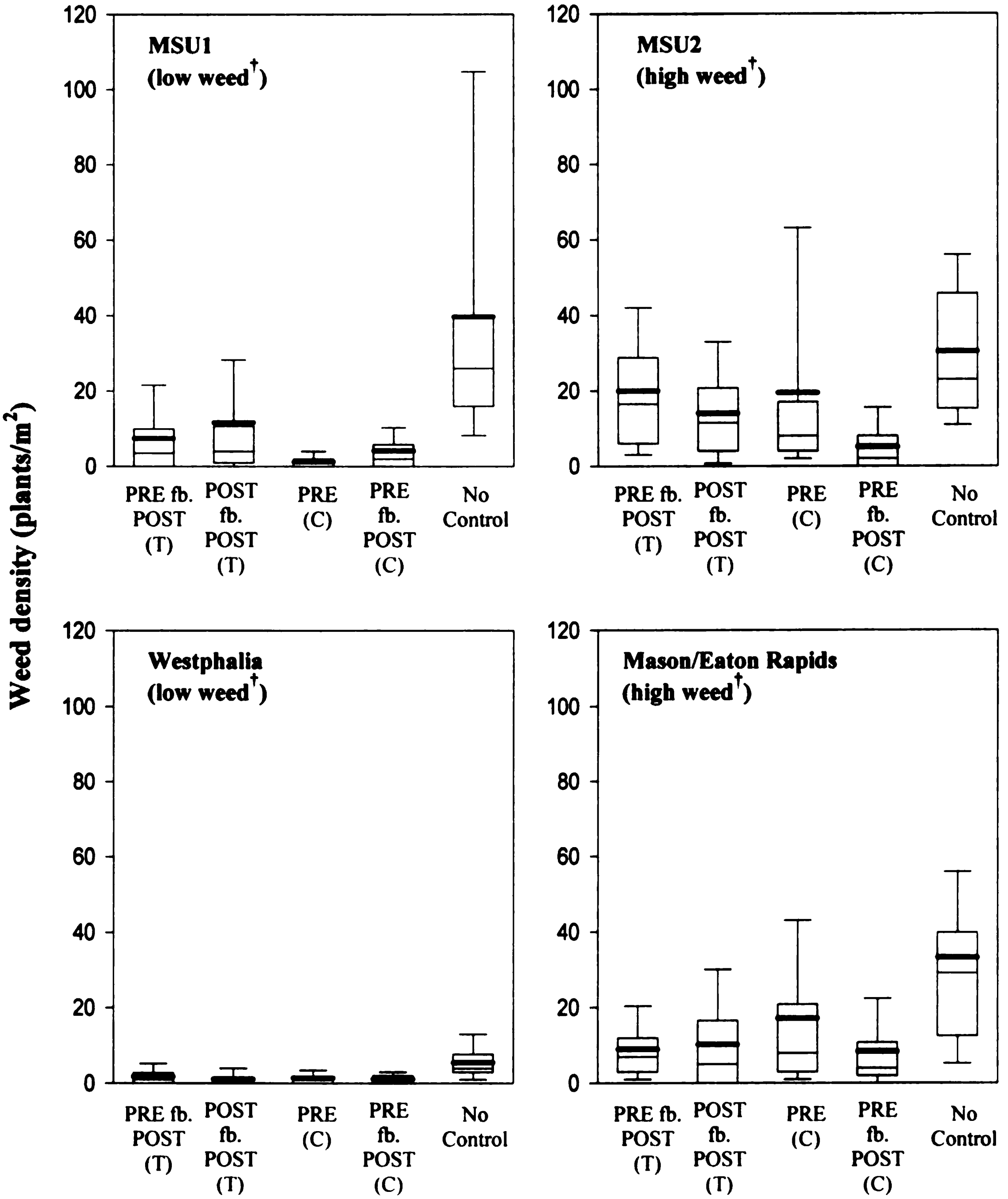

Figure 1. Boxplot figures representing total weed density (plants/m^2) at the end of the growing season at all four research sites. Data summarized from 2004, 2005, and 2006. Means of each treatment are indicated by the thicker black bar inside of each boxplot. The thinner black bar inside of each boxplot denotes the treatment median. The letter 'T' denotes a transgenic corn program for weed control that is based on the herbicide glyphosate; C, denotes a conventional herbicide program. Each herbicide treatment n=96 and no weed control n=72.

†Anticipated weed density based on field site history.

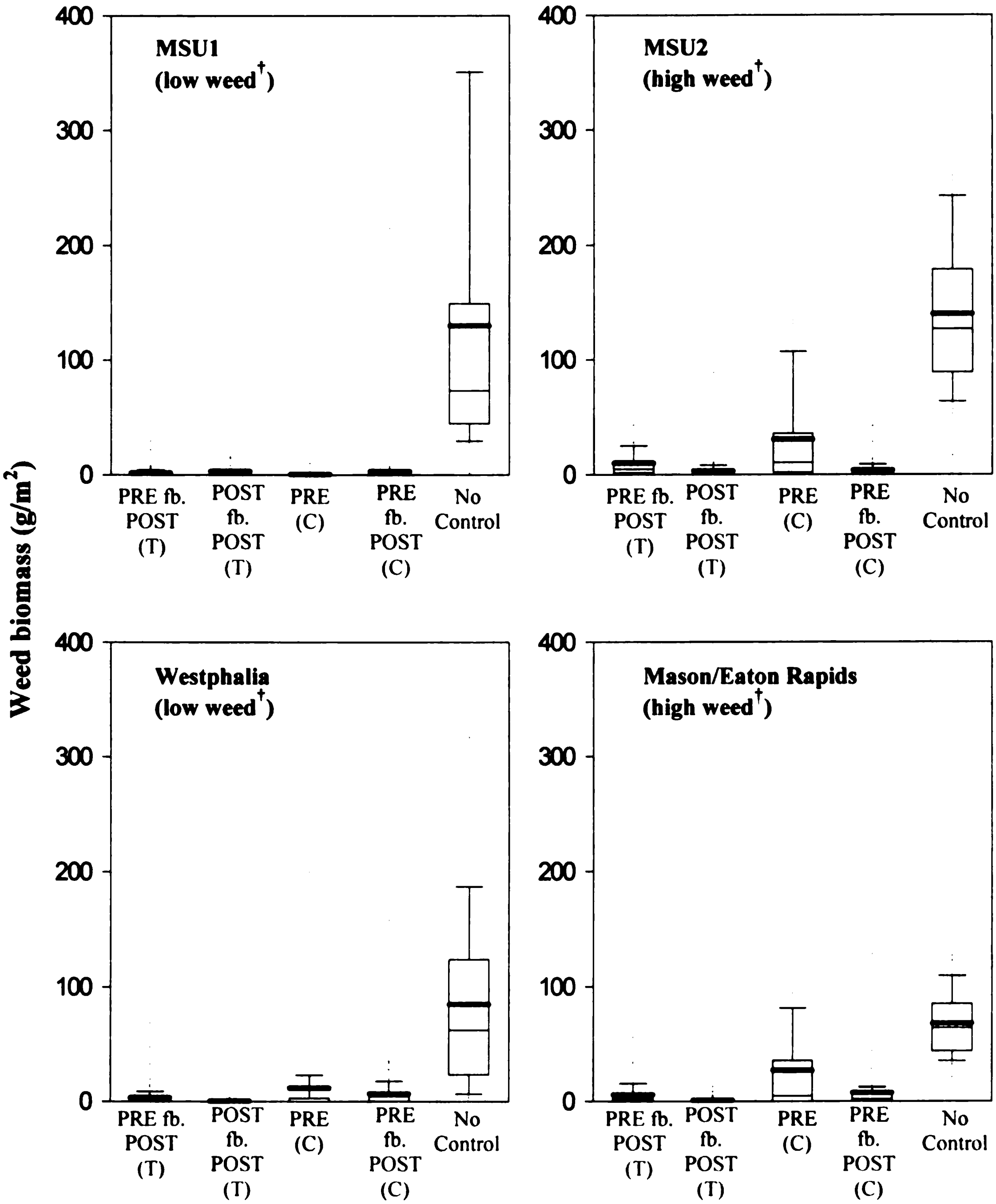

Figure 2. Boxplot figures representing total weed biomass (g/m^2) at the end of the growing season at all four research sites. Data summarized from 2004, 2005, and 2006. Means of each treatment are indicated by the thicker black bar inside of each boxplot. The thinner black bar inside of each boxplot denotes the treatment median. The letter 'T' denotes a transgenic corn program for weed control that is based on the herbicide glyphosate; C, denotes a conventional herbicide program. Each herbicide treatment n=96 and no weed control n=72.

†Anticipated weed density based on field site history.

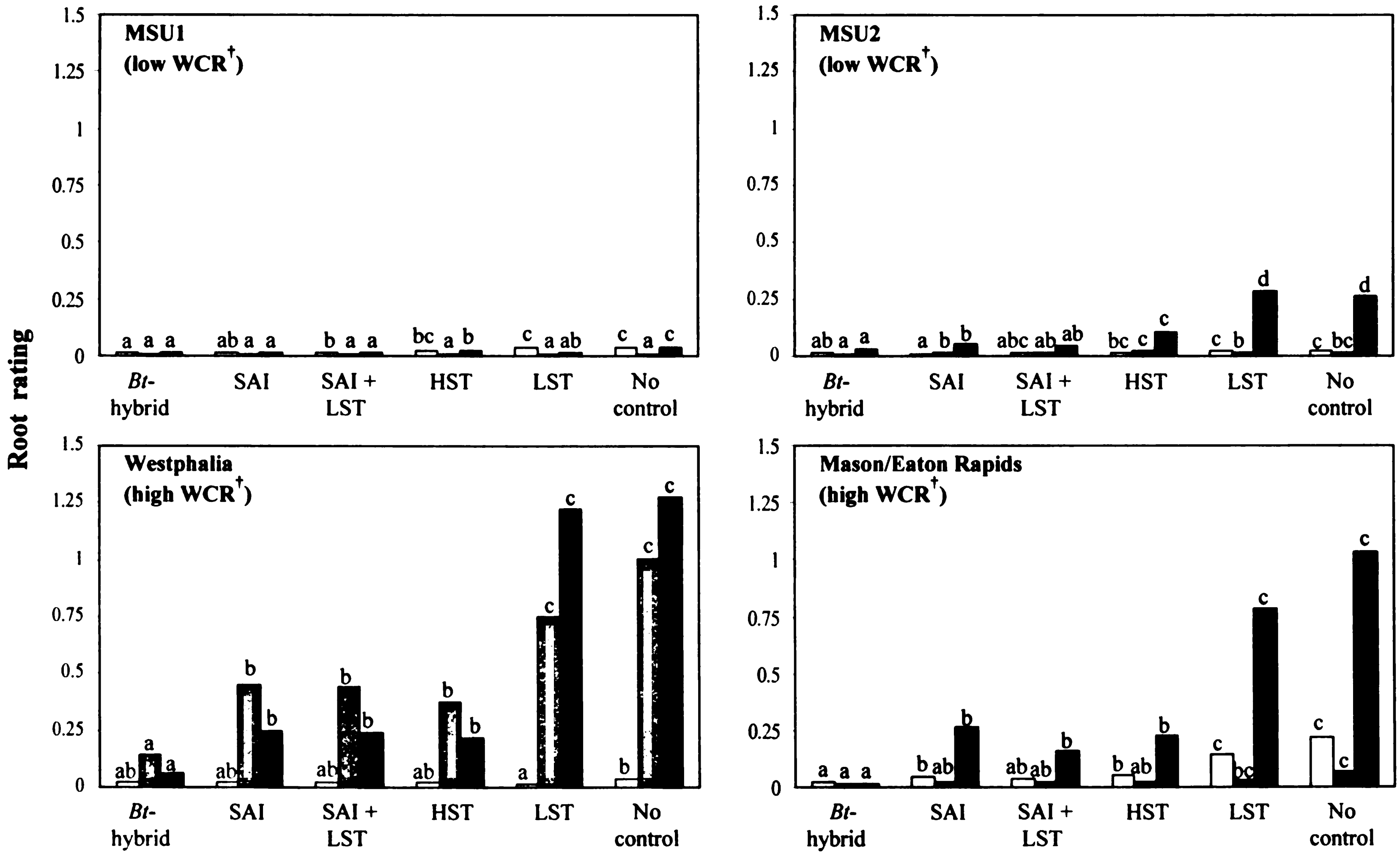

Figure 3. Corn root damage rating by WCR control programs‡ in 2004 (□), 2005 (■), and 2006 (■) at all locations.

Figure 3. (Continued)

Different lowercase letters indicate a significant difference ($\alpha = 0.05$) between treatments within a year.
Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST; high seed treatment.

† Anticipated WCR density based on field site history.

‡ SAI was the insecticide tefluthrin; LST was a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST was a commercial seed coating of clothianidin at 1.25 mg a.i./kernel. LST was not a WCR control program but was included for comparison as the transgenic *Bt*-hybrid was commercially available only with a LST of clothianidin.

CHAPTER II

Farm-Level Profitability of Transgenic Corn (*Zea mays* L.) Resistant to Both Glyphosate and Western Corn Rootworm (*Diabrotica virgifera virgifera* LeConte) in Michigan

ABSTRACT

The introduction of new transgenic traits offers corn (*Zea mays* L.) producers new options for weed and insect control. Many studies have investigated whether or not common resistance traits are economically justified. However, there are no records showing research results on the economic value of stacked or multiple resistance traits. The objective of this study was to determine the profitability of stacked trait corn hybrids by measuring the corn yield loss incurred from annual weeds and western corn rootworm (*Diabrotica virgifera virgifera* LeConte) (WCR) in comparison with conventional herbicide programs under varying corn rootworm and weed densities. Weed control costs were economically justified under both low and high weed densities. Gross margin gains relative to no weed control were reported for all weed control programs at all locations all years. Gross margin gains for the conventional herbicide programs were similar to the weed control programs based on the herbicide glyphosate. The presence and intensity of WCR larvae feeding on corn roots varied by year, and was less predictable than weed density. The overall gross margin of the no WCR control at the low WCR sites was often higher than the gross margins of the WCR control programs. This indicated that, unlike weed control, the cost associated with the control of WCR in many instances was not justified. At the high WCR sites, the cost of WCR control via either *Bt*-hybrid or conventional insecticide programs was justified in two of six site environments. In those two environments, the *Bt*-hybrid consistently had the highest gross margin gains relative to no WCR control. Gross margins were affected by corn yield more than by treatment costs. Gross margins were also greatly affected by commodity prices.

Planting corn hybrids that contain resistance traits for either glyphosate or corn rootworm does not necessarily mean greater profits. Growers should focus on yield potential by choosing high yielding corn hybrids adapted to local growing conditions.

Nomenclature: atrazine; glyphosate; mesotrione; s-metolachlor; clothianidin; tefluthrin; European corn borer, *Ostrinia nubilalis* Hübner; western corn rootworm, *Diabrotica virgifera virgifera* LeConte; corn, *Zea mays* L. 'DKC46-24', 'DKC46-28', 'DKC46-22', 'DKC47-10'.

Key Words: insect resistance, herbicide resistance, multiple resistance traits, transgenic, western corn rootworm, corn, profitability, gross margins.

Abbreviations: PRE, preemergence; POST, postemergence; fb., followed by; RR, glyphosate resistant; WCR, corn rootworm; ECB, European corn borer; *Bt*, *Bacillus thuringiensis*; HST, high seed treatment; LST, low seed treatment; SAI, soil-applied insecticide.

INTRODUCTION

Glyphosate-resistant (RR) corn (*Zea mays* L.) hybrids became commercially available in the USA in 1998 (Duke 2005). Corn hybrids expressing an insecticidal protein derived from the soil bacterium *Bacillus thuringiensis* spp. (*Bt*) were commercially introduced in the USA in 1996 to control the European corn borer (*Ostrinia nubilalis* Hübner) (ECB) (Ostlie et al. 1997). Corn hybrids expressing new insecticidal toxins to control corn rootworm (WCR) (*Diabrotica* spp.), were introduced in the United States in 2003 (Crowder et al. 2005). During the 2004 growing season, corn hybrids containing all three of the traits described above were commercialized. In the industry, the insertion of more than one resistance trait in a plant is commonly referred to as gene stacking. The development of stacked transgenic corn hybrids gives producers new options for controlling weeds and insects, but complicates hybrid selection.

Several economic studies have been published on weed control in glyphosate-resistant crops, including soybean (Johnson et al. 1997; Reddy 2003; Reddy and Whiting 2000; Webster et al. 1999), corn (Ferrell and Witt 2002; Hellwig et al. 2003; Johnson et al. 2000; Nolte and Young 2002), cotton (Askew and Wilcut 1999; Bailey et al. 2003; Culpepper and York 1999), sugarbeet (Kniss et al. 2004), and potato (Hutchinson et al. 2003). The corn studies concluded that net returns were similar for the glyphosate-based and conventional herbicide programs. Few researchers have documented the costs and returns associated with *Bt*-WCR hybrids (Crowder et al. 2005, 2006). Results indicated that where WCR rotation-resistant phenotypes exist, planting a *Bt* corn hybrid was the most economical strategy compared to conventional insecticides (Crowder et al. 2006). To date, as noted in Chapter 1, no such study has been conducted on corn hybrids containing multiple-resistance traits.

As with any new insect or weed management tactic, programs must be evaluated for both pest efficacy and economic return. The adoption of new practices is very dependent on economic considerations (Gianessi 2005). Growers choosing to use transgenic crops face additional seed costs associated with technology fees. In a survey conducted by Wilson et al. (2005), the technology fees associated with transgenic crops were one of the top concerns that growers had when using genetically modified corn.

Therefore, the objective of this study was to determine the profitability of stacked trait corn hybrids by assessing the value of corn yield, inputs costs, and refuge requirements and by measuring the corn yield loss incurred from weeds and WCR in comparison with conventional pest management programs under varying WCR and weed densities.

MATERIALS AND METHODS

Experimental Description. Field experiments were conducted in 2004, 2005 and 2006 at four locations each year as described in Chapter 1. There were two separate sites on the Crop and Soil Sciences Research Farm at Michigan State University (MSU) in East Lansing and two off-campus sites on commercial farms within 50 km of the MSU campus (Table 1). Sites were selected to reflect a range of weed density and WCR pressures experienced by MI producers. Experimental sites were chosen based on past history of pest infestation. High WCR density sites had a history of damage in corn planted after corn. Low WCR density sites were planted to corn in fields annually rotated between corn and soybean.

Near-isogenic corn hybrids[1] were used throughout the experiment to minimize agronomic differences. In 2004, two corn hybrids were used: 1) 'DKC46-28' with glyphosate resistance (RR) and 2) 'DKC46-24' with resistance to corn rootworm in addition to RR (WCR/RR). In 2005, a three-way stacked hybrid with resistance to ECB, WCR, RR was approved for commercial production in the US. Thus, in 2005 and 2006, we used isogenic hybrid lines with RR/ECB ('DKC47-10') and WCR/RR/ECB ('DKC46-24') to minimize experimental error attributable to ECB. Corn hybrids with the rootworm resistance traits ('DKC46-24' and 'DKC46-22') were available commercially only with a seed treatment of clothianidin[2] at a low dose (0.25 mg a.i./kernel) (LST) to control soil insects at planting. 'DKC46-28' and 'DKC47-10' were commercially available untreated or a low or high (1.25 mg a.i./kernel) (HST) dose of clothianidin.

All corn hybrids were planted in rows 0.76 m apart at a seeding rate of 74,000 seed/ha. Plots were four rows wide by 10.7 m long. The experimental design was a randomized complete block with four replications and 22 treatments (Table 2). The middle two rows of each plot were harvested with a plot combine at maturity. Corn grain yields were adjusted to 15.5% moisture. Treatments consisted of combinations of conventional insecticide and herbicide programs and *Bt*-corn/glyphosate-based weed and WCR management programs. Appropriate controls were included in the design of the experiment and consisted of combinations of weed (no weed control; weed free) and WCR (untreated; low dose of clothianidin (0.25 mg a.i/kernel; *Bt*-hybrid expressing Cry3Bb1) control programs. The control program with the low dose of clothianidin seed treatment was included because the *Bt*-hybrid was commercially only available with a low dose of the clothianidin seed treatment.

A weed control program based on glyphosate resistant corn using postemergence (POST) applications of glyphosate[3] and a conventional weed control program using selected herbicides to control weed species present were used throughout the study. Glyphosate-based weed management programs included (1) a preemergence (PRE) herbicide application of atrazine (0.91 kg ai/ha) plus S-metolachlor[4] (0.71 kg ai/ha) followed by a POST herbicide application of glyphosate (0.87 kg/ha), and (2) two separate POST herbicide applications of glyphosate (0.87 kg/ha each). All glyphosate applications included 2% (w/w) ammonium sulfate. Conventional management programs included (1) a PRE herbicide application of mesotrione (0.19 kg ai/ha) plus S-metolachlor (1.88 kg ai/ha) plus atrazine[5] (0.70 kg ai/ha), and (2) a PRE herbicide application of S-metolachlor[6] (1.39 kg ai/ha) followed by a POST herbicide application (determined by scouting for weed species and density). Herbicide treatments were applied with a tractor mounted, compressed-air sprayer calibrated to deliver 187 L/ha at 207 kPa through 8003 flat fan nozzles[7].

WCR control programs included (1) a hybrid expressing Cry3Bb1 *Bt*, (2) the conventional soil-applied granular insecticide (SAI) tefluthrin[8] applied in-furrow at a rate of 6.16 kg/ha, (3) a combination of the conventional SAI tefluthrin applied in-furrow at a rate of 6.16 kg/ha + a commercially applied seed treatment of clothianidin at a low rate (0.25 mg a.i./kernel) (LST), and (4) a commercially applied seed treatment of clothianidin at a high rate (1.25 mg a.i./kernel) (HST). The treatment combining the SAI + LST was included because the *Bt*-hybrid was commercially only available with a LST.

Profitability Analysis. The profitability analysis was based on gross margins over weed and insect control costs. Total control costs included herbicide treatment, insecticide treatment, application, and seed costs/technology fees. All other production costs were assumed to be fixed across treatments. Gross margins over total control costs were calculated by multiplying corn yield by corn price and subtracting total control costs.

Full suggested retail price for seed and pesticides (no discounts or promotional pricing) were used. Average pesticide prices for June 2006 were obtained from two major distributors within the state (Anonymous, 2006a). The technology fees were included in seed costs (Table 3). A technology fee of $37.04/ha (equivalent to $15/A) was subtracted from the treatments where no glyphosate was applied. Application cost of $14.82/ha (equivalent to $6/A) was determined by communicating with custom applicators throughout the state (Anonymous, 2006b). Application value was substantiated by referring to published custom machine work rates in Michigan (Dartt and Schwab 2002). The average rate for custom chemical application in Dartt and Schwab (2002) was $15.19/ha (equivalent to $6.15/A) and ranged from $9.88/ha to $41.98/ha (equivalent to $4/A to $17/A). All costs are summarized in Table 3. Gross margins were not calculated for weed free treatments due to the difficulty in assessing the value of hand-weeding.

Analysis per site per year. Historical corn prices from 1980-2005 were obtained from the National Agricultural Statistics Service (NASS). These historical values were discounted to adjust for inflation and the average of $ 0.10/kg (equivalent to $2.60/bushel) used for the gross margin analysis. Gross margins over weed and insect control costs for each site were statistically analyzed by year using ANOVA, and means were compared using Fisher's protected LSD ($\alpha = 0.05$) in SAS (SAS Institute 2007).

Sensitivity analysis by weed and WCR environment. The sensitivity analyses were conducted for corn prices of $60/Mg (equivalent to $1.50/bu), $100/Mg (equivalent to $2.50/bu), $140/Mg (equivalent to $3.50/bu), and $180/Mg (equivalent to $4.50/bu). The sensitivity analysis for the weed environments consisted of grouping the experimental sites by low or high weed density characteristics. The gross margin gains of the glyphosate-based weed control programs were evaluated relative to no weed control at the various price assumptions. The gross margin gains from the glyphosate-based and conventional weed control programs relative to no weed control were evaluated at a corn selling price of $100/Mg. This value was selected as it was the nearest to the historical discounted price. The sensitivity analysis for the WCR environments consisted of grouping the experimental sites by low or high WCR density characteristics. The gross margin gains of the *Bt*-corn hybrid were evaluated relative to no WCR control at the various price assumptions. The gross margin gains of the Bt-corn hybrid were evaluated relative to no WCR control for refuge requirements of 0%, 10%, and 20% at a corn selling price of $100/Mg. The gross margin gains from the *Bt*-corn hybrid and conventional WCR control programs relative to no WCR control were evaluated at a corn selling price of $100/Mg. Data were analyzed using the proc means statement in SAS (SAS Institute 2007) and gross margin gain means are presented with +/- 1 standard deviation.

RESULTS AND DISCUSSION

The gross margins for weed and WCR control treatments are presented in Figures 1 and 2. The values in these figures were calculated relative to the gross margins obtained when either no weed or no WCR control programs were utilized (Table 4). The greatest factor affecting gross margins was corn yield ($r^2 = 0.98$, data not shown) rather than treatment costs.

Gross margins affected by weed control. Gross margins increased for all weed control programs at all locations for the duration of the study (Figure 1). The use and cost of herbicides was economically justified (gain greater than 0) for all locations all years.

At MSU1, a low weed density site, there were no differences in gross margins among weed control programs in 2004, 2005, and 2006. Higher gross margins were noted in 2005 at MSU1 relative to 2004 and 2006 (Figure 1). This was due to the greater effect of uncontrolled weeds on corn yield (76.9%) in 2005, relative to 2004 and 2006 where the effect of weeds on corn yield was 30.2% and 38.1%, respectively (data not shown). This was also reflected in the lower gross margin value obtained for the no weed control treatment in 2005 (Table 4). At Westphalia, there were no differences in gross margins among weed control programs in 2005 and 2006 (Figure 1). In 2004, the plots receiving the conventional PRE herbicide program had significantly higher gross margins gains than the plots receiving the conventional PRE fb. POST herbicide program. The higher gross margin gains in the conventional PRE herbicide program may be attributable to it being the only program that did not include the costs associated with a second herbicide application. Overall, at the low weed density sites, the glyphosate-based PRE fb. POST, POST fb. POST, and the conventional PRE herbicide programs resulted in gross margins not significantly different from the highest gross margins in six of six environments. The conventional PRE fb. POST herbicide program had gross margins that were similar to the highest gross margins in five of six environments.

The highest gross margin gains relative to no weed control were observed at MSU2 (Figure 1). This is the site where the impact of uncontrolled weeds on corn yields was the highest at 76%, 89%, and 95% in 2004, 2005, and 2006, respectively (data not shown). This is also reflected in the low and sometimes negative gross margin of the no weed control treatments (Table 4). In 2004, the glyphosate-based PRE fb. POST herbicide program and conventional PRE herbicide program had the highest gross margins, followed by the conventional PRE fb. POST herbicide program, and the glyphosate-based POST fb. POST herbicide program. However, these differences were not consistent across years (Figure 1). In 2005, the only treatment that had gross margins significantly lower than the highest gross margins was the conventional PRE fb. POST herbicide program (Figure 1). At MSU2 in 2006, there were no differences in gross margins among any of the weed control programs. At Mason/Eaton Rapids in 2004, the conventional PRE herbicide program had the highest gross margin and the glyphosate-based POST fb. POST herbicide program resulted in the lowest gross margin gains. In 2005, there were no differences in gross margins among weed control programs. In 2006, the conventional PRE herbicide program had gross margins significantly lower than the other weed control programs, which is what was anticipated for these high weed density sites. As described above, there were inconsistencies in the gross margins of the conventional PRE herbicide program from year to year. Preemergence soil applied herbicides allow for critical early season weed control (Gonzini et al. 1999) but often the residual activity of these products is not sufficient to provide adequate, season-long weed control, which has the potential of jeopardizing corn yield (Rabaey and Harvey 1997; Spandl et al. 1997) and inherent profitability. Soil-applied herbicides are highly dependent on rainfall shortly after application in order to activate the herbicide (Walker and Roberts 1975). Too little rainfall and the herbicides are not sufficiently activated and too much rainfall causes the herbicide to leach past the critical weed seed germination zone. In summary, at the high weed density sites, the glyphosate-based PRE fb. POST herbicide program was the only weed control program to have gross margins similar to the highest gross margins in all six of six site environments. The conventional PRE fb. POST herbicide program had gross margins that were similar to the highest gross margins in five of six environments. The conventional PRE herbicide program had high gross margins in five of six environments.

Generic glyphosate products are widely available in the marketplace. An analysis was conducted for weed control programs where the glyphosate-based programs included glyphosate costs at either $2.64/L or $5.28/L (equivalent to $10/gal and $20/gal, respectively). The use of generic glyphosate in lieu of more expensive brand-name products did increase the GM of the glyphosate-based weed control programs. The reduction in herbicide costs from using a generic glyphosate product was not sufficient to create differences between the GM of the glyphosate-based and conventional weed control programs (data not shown). Despite, there being no differences between the GM of the glyphosate-based and conventional weed control programs, growers would likely purchase the lower cost glyphosate product assuming the efficacy of weed control was identical. For the PRE fb. POST (i.e. 1 application of glyphosate), the use of a generic glyphosate product would reduce herbicide input costs by $8.12/ha and $12.52/ha for product prices of $5.28/L or $2.64/L, respectively. For the glyphosate-based POST fb. POST herbicide program, the use of a generic glyphosate product would reduce herbicide input costs by $16.25/ha and $25.04/ha for product prices of $5.28/L or $2.64/L, respectively. Furthermore, under low weed density environments, growers in Michigan often employ a single POST application of glyphosate to control weeds. This weed control program would allow growers to further cut input costs by eliminating fees associated with a second application of glyphosate.

The sensitivity analysis for both the PRE fb. POST and POST fb. POST glyphosate-based weed control programs showed similar results (Figures 3 and 4). Gross margin gain means relative to no weed control were positive for all price assumptions under both low and high weed environments. Also, as one would expect, larger gains were noted with the higher corn prices. Similar gross margins gains were achieved using the four weed control programs (Figure 5) and the additional cost of weed control or technology fees were justified under both low and high weed densities.

Gross margins affected by WCR control. The presence and intensity of WCR larvae feeding on corn roots varied by site and year and was less predictable than weed density. The overall gross margins of the no WCR control treatments (Table 4) at MSU1 and MSU2, the rotated sites, were often higher than the gross margins of the WCR control programs (Figure 2). This indicated that, unlike weed control, the cost associated with the control of WCR in many instances was not justified. At MSU1 in 2004 and 2005, all WCR control treatments incurred losses relative to no insect control. These results were expected with the anticipated low WCR sites. There were no differences in gross margins from treatments in 2004 and 2005, with the exception of the HST in 2005. In 2005, the HST resulted in the greatest losses relative to the other treatments and the lowest gross margins of any treatment at all locations (Figure 2). This treatment resulted in a significant stand reduction in corn population at all locations in 2005. The lower gross margins observed with the HST may be a reflection of lower yields due to the observed stand loss. The stand loss is likely related to the seed treatment process. Even though MSU2 was a low WCR density site, an increased effect of the insect on corn yield throughout the duration of the study was observed (data not shown). This increase in WCR density may explain why use of the *Bt*-hybrid resulted in the largest gross margin gains relative to the conventional WCR control programs in both 2005 and 2006 (Figure 2). In 2006, losses were only incurred when the SAI was used. However, in 2004 and 2005 the use of SAI resulted in gross margins that did not differ from the highest gross margins

(Figure 2). In summary, at the low WCR density sites, the *Bt*-hybrid resulted in gross margin gains in three of six environments. However, the *Bt*-hybrid only had significantly greater gross margins than the other control programs in one of six environments. In most instances, the use of a WCR control program was not justified as the gross margin with no control was often greater than the gross margins with the WCR control programs.

Despite both Westphalia and Mason/Eaton Rapids being our anticipated high WCR sites, varying impacts of WCR on corn yields were observed, and consequently on gross margins. In 2004 at Westphalia, there were no differences in gross margins among WCR treatments (Figure 2). Furthermore, all WCR control methods recorded losses relative to the no WCR control. This indicates that control of the insect was not necessary at Westphalia in 2004. Spring rainfall three times above the monthly average in the Mid-Michigan area may have played a role in the lack of WCR injury at Westphalia. Excess precipitation could have possibly compromised the anticipated high WCR density by drowning the larvae (MacDonald and Ellis 1990) at Westphalia during the 2004 growing season. Planting was delayed at both Westphalia and Mason/Eaton Rapids in 2004 (Table 1). Hoffmann et al. (2000) found that delayed planting dates may play a role in larval mortality due to the lack of corn. This circumvents a time period in which peak rootworm larval populations and the younger, more susceptible, growth phase of corn typically coincide (Carlson and Gauge 1989). However, there were clear economic advantages at Westphalia in 2005 and 2006 for utilizing any WCR control program (Figure 2). In both 2005 and 2006, the highest gross margins relative to no WCR control were recorded with use of the

Bt-hybrid. The trend in gross margins was similar in both 2005 and 2006, the *Bt*-hybrid consistently had the highest gross margins gains, followed by the SAI and SAI + LST, and the HST. Among the conventional WCR control treatments, those programs that included the SAI resulted in similar gross margins and both were greater than the HST (Figure 2).

At Mason/Eaton Rapids the transgenic *Bt*-hybrid was the only WCR control program that showed gains relative to no WCR control in 2004 and 2006, but there were no differences in gross margins with the other WCR control programs (Figure 2). In 2005, the HST resulted in gross margins significantly lower than the highest gross margins (Figure 2) which may be attributable to the stand loss incurred from this treatment. Although fields near Mason/Eaton Rapids had an anticipated high WCR density, the additional costs associated with the control of the insect were not justified because the actual WCR densities were much lower than anticipated. In summary, at the anticipated high WCR density sites, the cost of WCR control via either the *Bt*-hybrid or conventional insecticide programs was justified in two of six environments. In those two environments, use of the *Bt*-hybrid consistently resulted in the highest gross margin gains relative to no WCR control.

The sensitivity analysis examined the value of *Bt* corn relative to no WCR control which varied by WCR density (Figure 6). Regardless of corn price, the *Bt* GM means were always negative at the low WCR density environments (Figure 6). At the high WCR density, a negative GM mean for *Bt* was noted only for the $60/Mg corn price. Positive GM gains, relative to no WCR control, were noted for $100/Mg, $140/Mg, and $180/Mg corn prices at high WCR density (Figure 6). This follows the fact that it becomes more manageable to cover input costs as commodity prices increase. Currently, growers are required to plant a 20% refuge either within or adjacent to a WCR-resistant corn field as a method to manage the development of insect resistance. The application soil insecticides to control WCR larvae are acceptable on refuge acres. At the $100/Mg corn price, the *Bt* GM means were negative at the low and positive at the high WCR densities regardless of the size of the refuge (Figure 7). Under both low and high WCR densities the highest means were for no refuge and the lowest for 20% refuge (Figure 7). Despite the inclusion of costs associated with a 20% refuge, the *Bt*-corn hybrid had the highest mean gains of all WCR control programs under high WCR density (Figure 8). Costs associated with the use of *Bt*-corn were justified under high but not low WCR densities.

In conclusion, similar gross margins were achieved using the four weed control programs and the additional cost of weed control or technology fees were justified at all locations all years. In contrast, the cost associated with the control of WCR was only justified in three of twelve environments, once at the low and twice at the high WCR sites, respectively. In those three environments, use of the *Bt*-hybrid resulted in significantly greater gross margins than using the conventional WCR control programs. This indicated that, unlike weed control, the cost associated with the control of WCR in many instances was not justified. It is important to consider that the cost of technology fees associated with transgenic traits vary by region. The profitability of corn hybrids resistant to glyphosate and WCR, assessed under realistic field conditions, may be one of the key criteria for the adoption of these stacked traits. However, non-pecuniary costs, such as pesticide applicator safety for example, may also play a role in their adoption by certain corn growers. The use of a 20% refuge, despite being treated with SAI, resulted in slightly lower profits for growers compared to using only *Bt* corn. Relative to other WCR control programs, greater gains were reported for the *Bt*-corn hybrid even when the latter included costs associated with a 20% refuge. The use of refugia should be supported as the best management practice in implementing a resistance management plan. The implementation of refugia and resistance monitoring will become more and more important as grower adoption increases and exposure of WCR larvae over multiple growing seasons accrues. Furthermore, growers should be encouraged to scout for WCR adults in fields (or land adjacent to fields) where corn will be planted the following season and then base their management action on scouting observations than relying solely on prophylactic pest control programs. From this study we observed that gross margins reflected trends in corn yield rather than following costs associated with specific treatments. Resistance to glyphosate or corn rootworm in a corn hybrid does not necessarily mean greater profits. Growers should focus on the yield potential of the crop by choosing high yielding hybrids adapted to local growing conditions and closely monitor for the presence and density of pests.

Sources of Materials

[1] Dekalb Genetics Corp., Monsanto Company, St. Louis, MO 63167

[2] Poncho 600, Bayer CropScience, Research Triangle Park, NC 27709

[3] Roundup WeatherMax, Monsanto Company, St. Louis, MO 63167

[4] Bicep II Magnum, Syngenta Crop Protection, Inc. Greensboro, NC 27409

[5] Lumax, Syngenta Crop Protection, Inc. Greensboro, NC 27409

[6] Dual II Magnum, Syngenta Crop Protection, Inc. Greensboro, NC 27409

[7] TeeJet Spraying Systems Co., Wheaton, IL 60188

[8] Force 3G, Syngenta Crop Protection, Inc. Greensboro, NC 27409

[9] SAS Institute Inc., Cary, NC 27513

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Table 1. Anticipated weed and corn rootworm (WCR) density levels, soil characteristics, and planting dates at each location in 2004, 2005, and 2006.

Site	Year	Location	Annual weed density†	WCR density†	Soil texture	Soil pH	Soil OM	Planting date
1	2004				Clay Loam	7.4	2.3	April 30
	2005	MSU1	LOW	LOW	Sandy Loam	6.5	1.1	May 4
	2006				Sandy loam	6.6	1.0	April 29
2	2004				Clay Loam	7	3	May 17
	2005	MSU2	HIGH	LOW	Clay Loam	6.7	2.6	May 5
	2006				Clay Loam	6.6	2.4	May 4
3	2004				Sandy Loam	5.8	2.2	June 4
	2005	Westphalia	LOW	HIGH	Clay Loam	7	2.4	May 4
	2006				Loam	7.5	2.6	April 29
4	2004	Mason			Sandy loam	6.7	2.9	June 4
	2005	Eaton Rapids	HIGH	HIGH	Loam	6.3	3	May 4
	2006	Mason			Sandy Loam	7.1	2.6	April 29

†Anticipated pest densities based on field history.

Table 2. Treatments combining weed and corn rootworm management programs, Michigan (2004-2006).

Trt	Weed control programs		Corn rootworm control programs	
	Type[a]	Description	Type[a]	Description
1	PRE fb. POST (T)	atrazine + s-metolachlor fb. glyphosate	*Bt*-hybrid (T)	Hybrid resistance + clothianidin
2	POST fb. POST (T)	glyphosate fb. glyphosate	*Bt*-hybrid (T)	Hybrid resistance + clothianidin
3	PRE (C)	mesotrione + s-metolachlor + atrazine	*Bt*-hybrid (T)	Hybrid resistance + clothianidin
4	PRE fb. POST (C)	s-metolachlor fb. POST (scouting)	*Bt*-hybrid (T)	Hybrid resistance + clothianidin
5	none	No weed control	*Bt*-hybrid (T)	Hybrid resistance + clothianidin
6	none	Weed free	*Bt*-hybrid (T)	Hybrid resistance + clothianidin
7	PRE fb. POST (T)	atrazine + s-metolachlor fb. glyphosate	SAI[†] (C)	tefluthrin
8	PRE fb. POST (T)	atrazine + s-metolachlor fb. glyphosate	SAI + LST[†] (C)	tefluthrin + clothianidin
9	PRE fb. POST (T)	atrazine + s-metolachlor fb. glyphosate	HST[†] (C)	clothianidin
10	POST fb. POST (T)	glyphosate fb. glyphosate	SAI (C)	tefluthrin
11	POST fb. POST (T)	glyphosate fb. glyphosate	SAI + LST (C)	tefluthrin + clothianidin
12	POST fb. POST (T)	glyphosate fb. glyphosate	HST (C)	clothianidin
13	PRE (C)	mesotrione + s-metolachlor + atrazine	SAI (C)	tefluthrin
14	PRE (C)	mesotrione + s-metolachlor + atrazine	SAI + LST (C)	tefluthrin + clothianidin
15	PRE (C)	mesotrione + s-metolachlor + atrazine	HST (C)	clothianidin
16	PRE fb. POST (C)	POST (scouting)	SAI (C)	tefluthrin
17	PRE fb. POST (C)	POST (scouting)	SAI + LST (C)	tefluthrin + clothianidin
18	PRE fb. POST (C)	POST (scouting)	HST (C)	clothianidin
19	none	No weed control	none	No insect control
20	none	No weed control	LST (C)	clothianidin
21	none	Weed free	none	No insect control
22	none	Weed free	LST (C)	clothianidin

[a] Abbreviations: PRE, preemergence; POST, postemergence; fb., followed by; SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic corn program for either weed or insect control; C, denotes a conventional herbicide or insecticide program.

[†] SAI was the soil applied insecticide tefluthrin; LST was a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST was a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

Table 3. Cost assumptions used in profitability analysis.

Custom application cost for herbicides	$14.81/ha
Herbicide costs[a,b]	
PRE fb. POST (T)	$43.88/ha
POST fb. POST (T)	$37.28/ha
PRE (C)	$66.99/ha
PRE fb. POST[c] (C)	$59.16/ha – $105.43/ha
Insecticide costs	
SAI tefluthrin	$48.22/ha
LST clothianidin (0.25 mg a.i./kernel)	$15.73/ha
HST clothianidin (1.25 mg a.i./kernel)	$45.98/ha
Seed Costs	
'DKC47-10'[d]	$150.84/ha
'DKC46-22'[e]	$169.83/ha
Technology fee for glyphosate resistance[f]	$37.04/ha

[a] All herbicide costs include the recommended additives.

[b] Abbreviations: PRE, preemergence; POST, postemergence; fb., followed by; SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a weed control program based on the herbicide glyphosate; C, denotes a conventional herbicide program.

[c] Conventional POST herbicide program varied by location based on weed species present.

[d] Resistant to glyphosate and European corn borer.

[e] Resistant to corn rootworm, glyphosate, and European corn borer.

[f] Included in the seed costs.

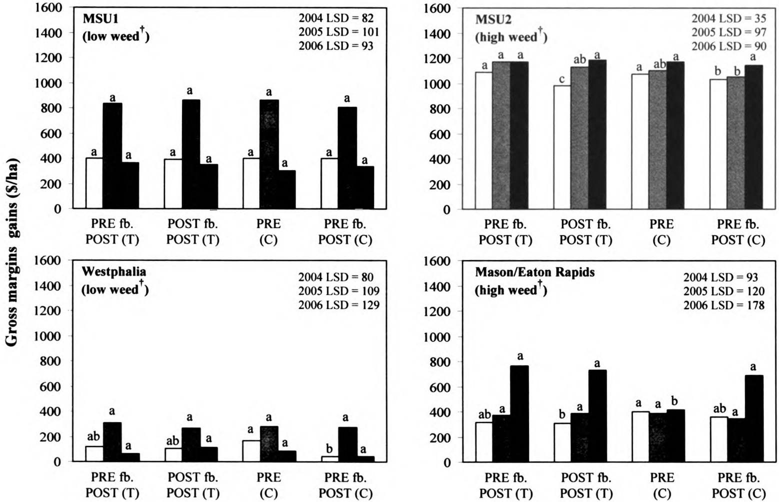

Figure 1. Gross margins gains of weed control programs relative to no weed control (= 0) in 2004 (□), 2005 (■), and 2006 (■) at all locations. The letter 'T' denotes a glyphosate-based herbicide program and 'C' denotes conventional herbicide program.

Figure 1. (Continued)

Different lowercase letters indicate a significant difference ($\alpha = 0.05$) between herbicide programs within a year.
† Anticipated weed density based on field site history.

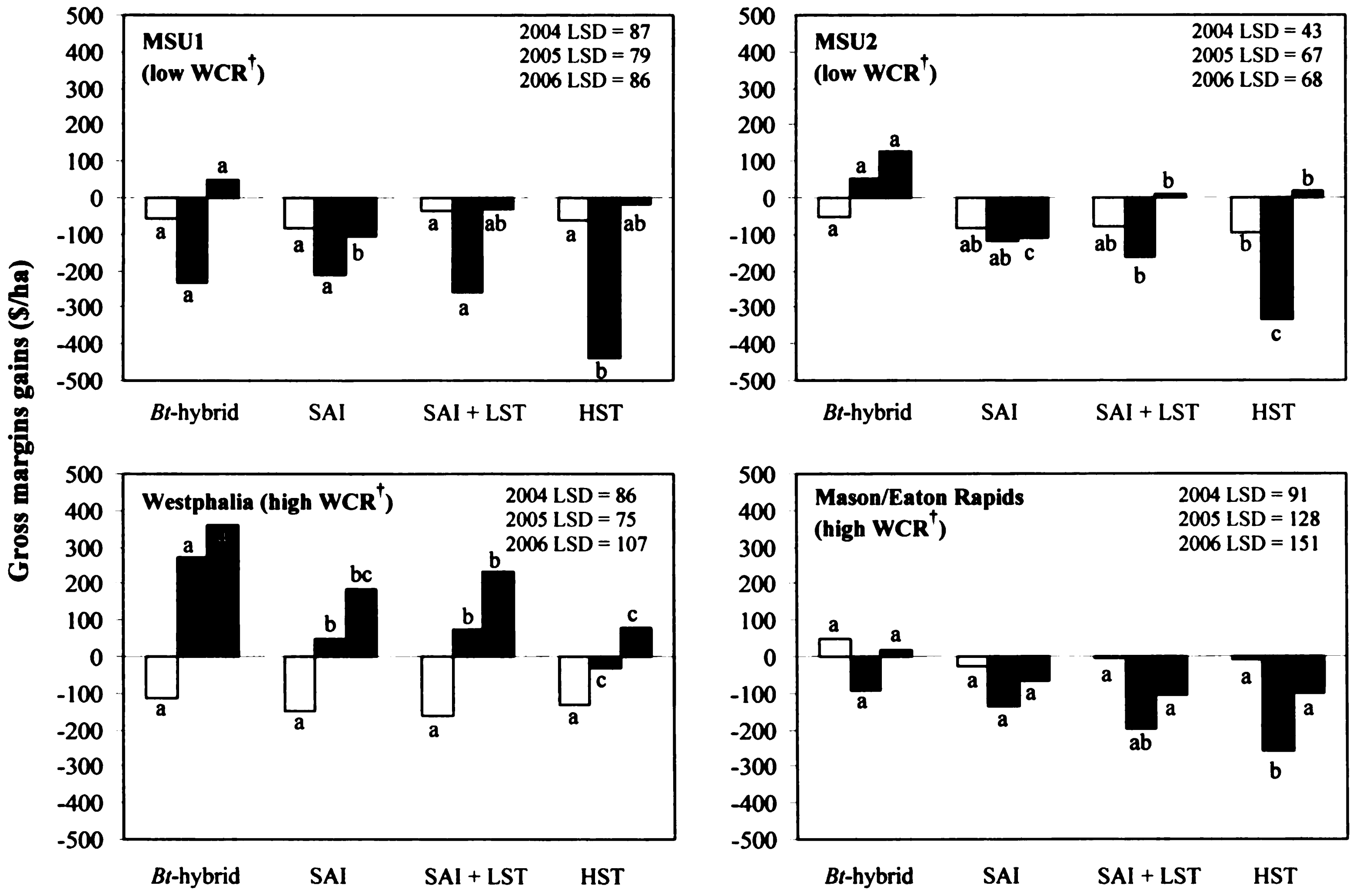

Figure 2. Gross margins gains of WCR control programs‡ relative to no insect control (= 0) in 2004 (□), 2005 (■), and 2006 (■) at all locations.

Figure 2. (Continued)

Different lowercase letters indicate a significant difference ($\alpha = 0.05$) between treatments within a year.

† Anticipated WCR density based on field site history.

‡ SAI was the soil applied insecticide tefluthrin; LST was a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST was a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

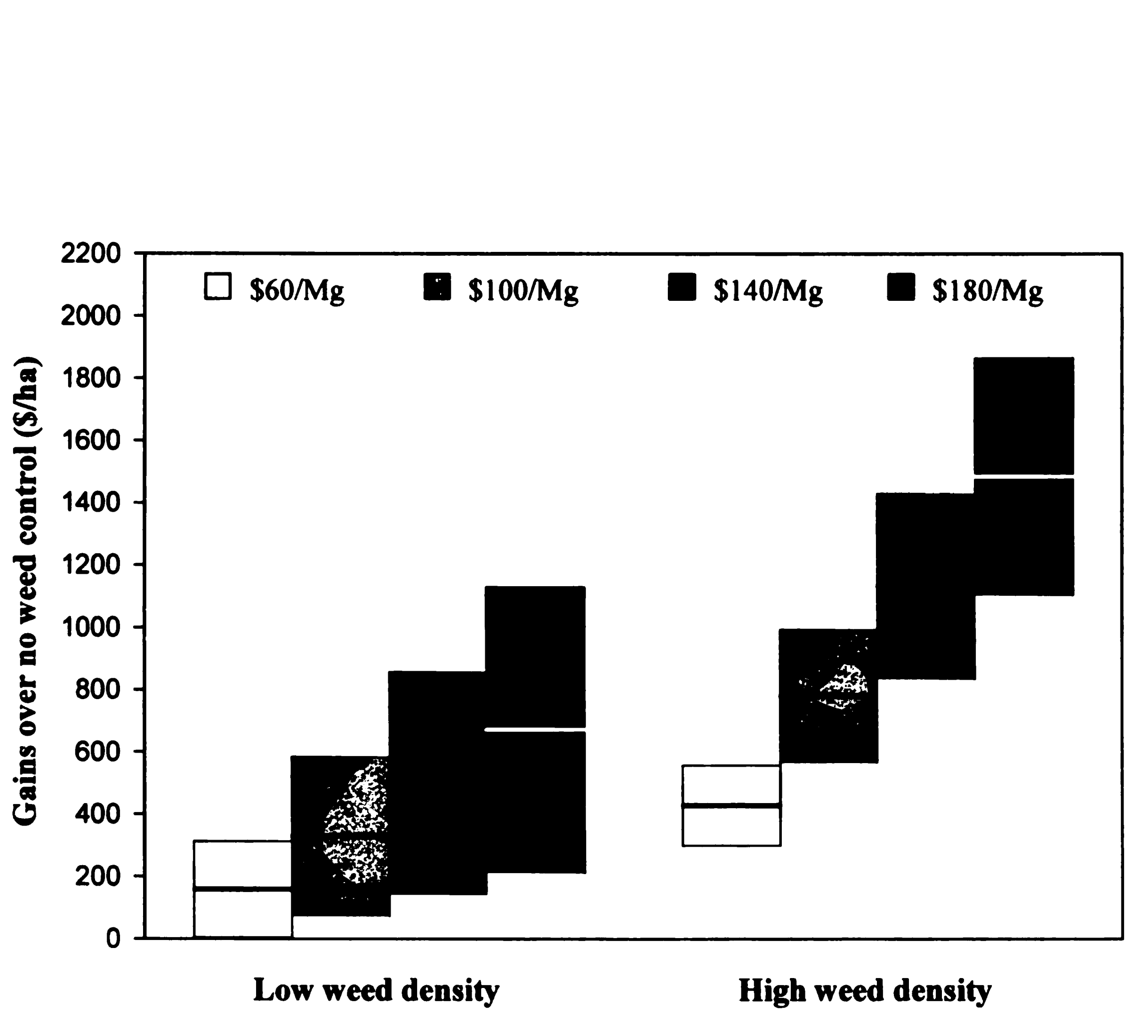

Figure 3. Sensitivity analysis of gross margin gains from the sequential (PRE fb. POST), glyphosate-based weed control program by weed density and corn price ($/Mg) in comparison to no weed control ($/ha means ± 1 standard deviation). The horizontal line in the bars represents the mean.

[a] Abbreviations: fb., followed by; PRE, preemergence; POST, postemergence.

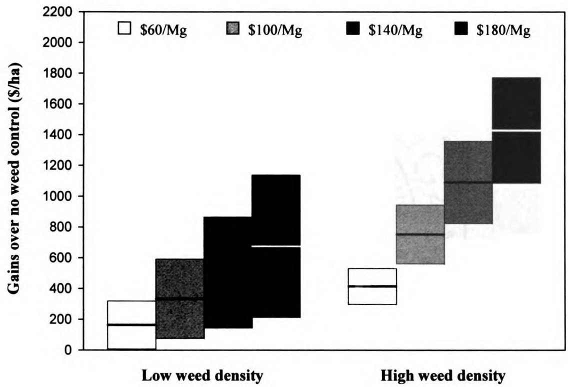

Figure 4. Sensitivity analysis of gross margin gains from the glyphosate fb. glyphosate weed control program by weed density and corn price ($/Mg) in comparison to no weed control ($/ha means ± 1 standard deviation). The horizontal line in the bars represents the mean.

[a] Abbreviation: fb., followed by.

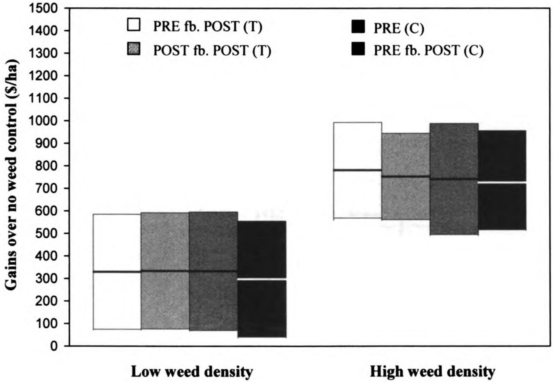

Figure 5. Analysis of gross margin gains from glyphosate-based and conventional weed control programs by weed density in comparison to no weed control ($/ha means ± 1 standard deviation). The horizontal line in the bars represents the mean.

[a] Abbreviations: PRE, preemergence; POST, postemergence; fb., followed by; T, denotes a transgenic corn program for weed control that is based on the herbicide glyphosate; C, denotes a conventional herbicide program.

[b] Assumes corn selling price of $100/Mg.

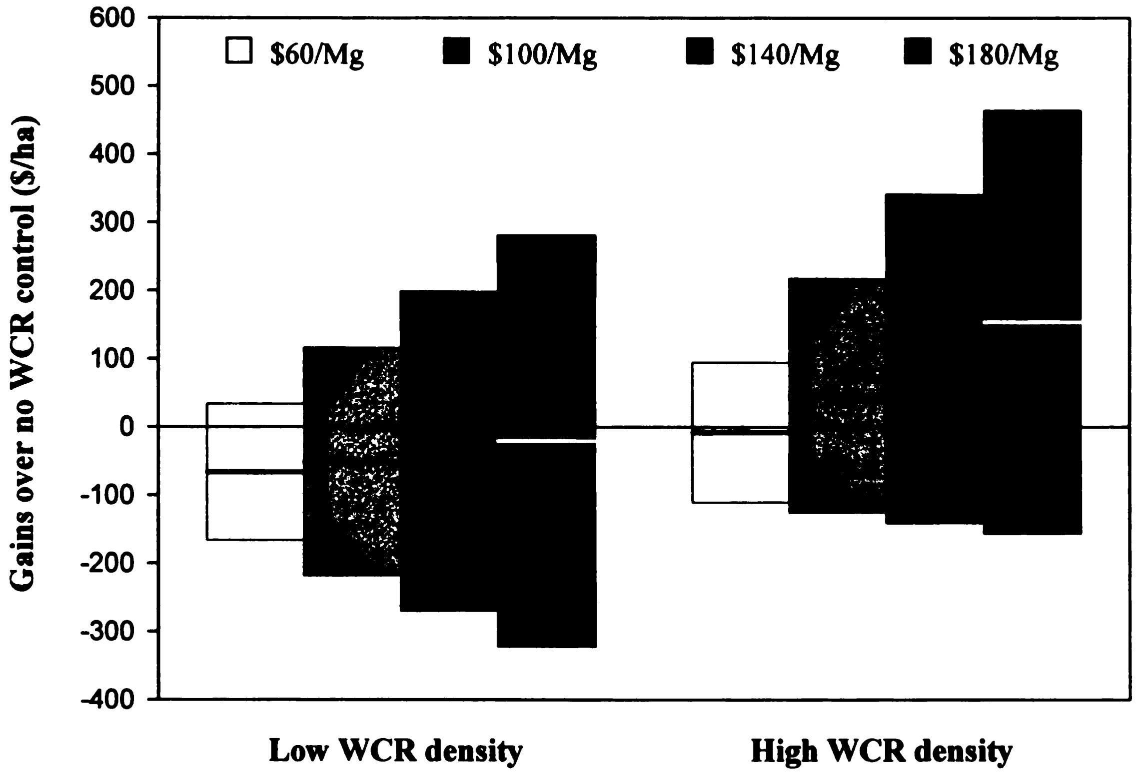

Figure 6. Sensitivity analysis of gross margin gains from *Bt*-corn (assuming 20% refuge) by WCR density and corn price ($/Mg) in comparison to no WCR control ($/ha means ± 1 standard deviation). The horizontal line in the bars represents the mean.

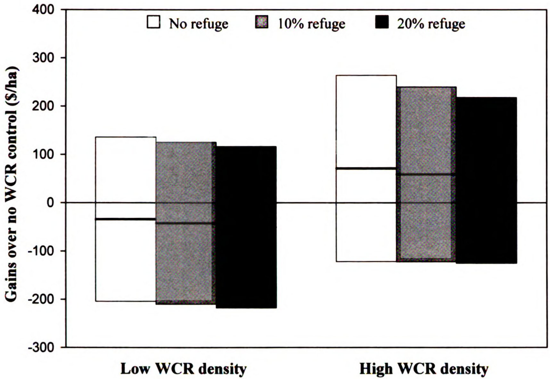

Figure 7. Analysis of gross margin gains from *Bt*-corn by WCR density under varying refuge requirements (no refuge, 10% refuge, 20% refuge) in comparison to no WCR control ($/ha means ± 1 standard deviation). The horizontal line in the bars represents the mean.

[a] Assuming corn selling price of $100/Mg.

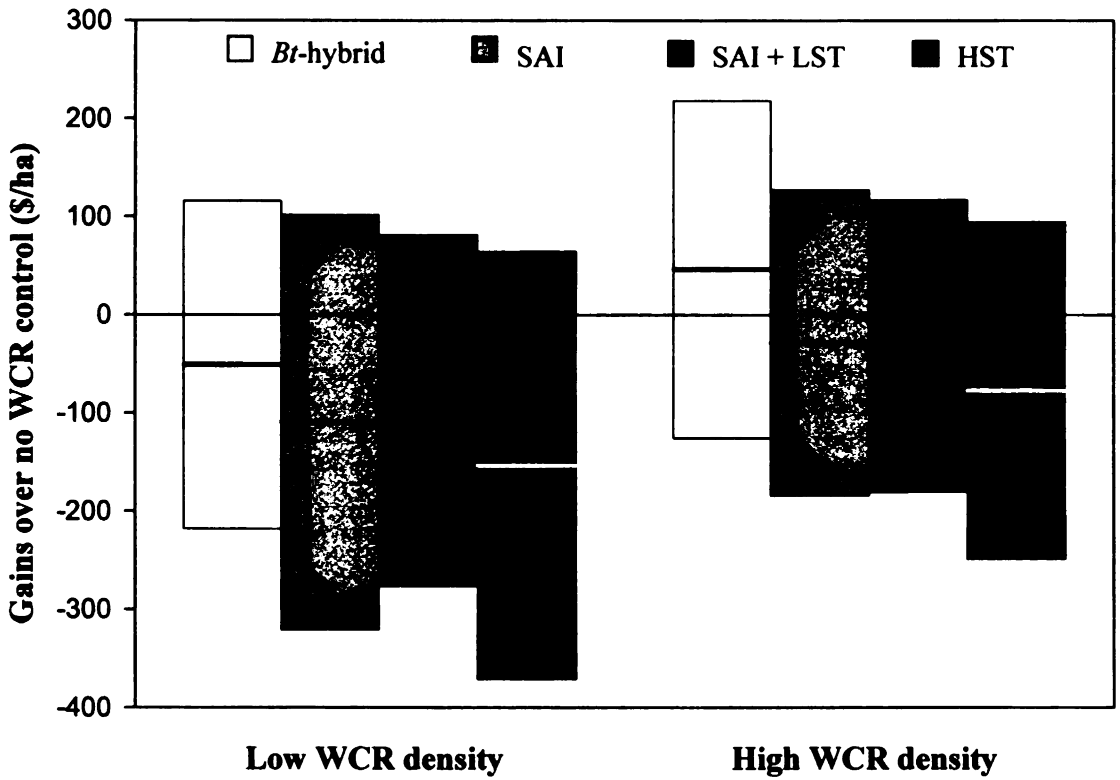

Figure 8. Analysis of gross margin gains from *Bt*-corn (assumes 20%refuge) and conventional WCR control programs (SAI, SAI + LST, HST) by WCR density in comparison to no WCR control ($/ha means ± 1 standard deviation). The horizontal line in the bars represents the mean.

[a] Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment.

[b] Assuming corn selling price of $100/Mg.

APPENDIX

Table 1. Gross margins[†] ($/ha) for no weed and no WCR control in 2004, 2005, and 2006 at all locations.

	MSU1	MSU2	Westphalia	Mason/Eaton Rapids
	$/ha			
No weed control				
2004	961.63	179.28	694.27	480.20
2005	141.21	2.17	347.65	469.60
2006	494.25	-97.31	754.64	125.28
No CRW control				
2004	1418.94	1299.78	941.98	821.33
2005	1268.89	1284.74	539.01	1011.91
2006	861.09	1052.17	614.72	859.11

[†]Gross margin values were used to make relative comparisons with the weed and insect control treatments in Figures 1 and 2 (Chapter 2).

Table 2. Costs[†] ($/unit) of additives, herbicides, and insecticides used in the weed and insect control programs.

Product name	Costs ($/unit)
28% nitrogen	1.37/gallon
Ammonium sulfate	0.19/lb
Activator 90	6.20/gallon
Atrazine 4L	9.44/gallon
Atrazine 90DF	2.17/lb
Bicep II Magnum	38.95/gallon
Buctril 2EC	64.35/gallon
Callisto	530.36/gallon
Clarity	89.89/gallon
Crop oil concentrate	6.20/gallon
Distinct	41.13/lb
Dual II Magnum	95.59/gallon
Force 3G	4.34/lb
Herbimax	6.20/gallon
Hornet WDG	52.04/lb
Lumax	43.40/gallon
Methylated seed oil	10.12/gallon
Option	9.27/oz
Permit	16.27/oz
Resource	163.31/gallon
Roundup Weathermax	39.17/gallon
Steadfast	21.08/oz
Steadfast ATZ	20.59/lb

[†] June 2006 average price obtained from two distributors.

Table 3. Gross margins for insect control programs at MSU2 for varying refuge requirements at a corn selling price of $60/Mg.

Year	WCR control program [a,b]	No refuge		10% refuge		20% refuge	
		\$/ha					
2004	*Bt*-hybrid (T)	622	a	619	a	616	a
	SAI (C)	592	b	592	b	592	ab
	SAI + LST(C)	588	b	588	b	588	b
	HST (C)	584	b	584	b	584	b
	LSD(0.05)[c]	26		25		25	
2005	*Bt*-hybrid (T)	609	a	603	a	598	a
	SAI (C)	550	b	550	b	550	b
	SAI + LST (C)	526	b	526	b	526	b
	HST (C)	436	c	436	c	436	c
	LSD(0.05)	40		40		40	
2006	*Bt*-hybrid (T)	589	a	572	a	554	a
	SAI (C)	440	c	440	c	440	c
	SAI + LST (C)	495	b	495	b	495	b
	HST (C)	511	b	511	b	511	b
	LSD(0.05)	35		35		35	

[a]Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[b]SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[c]Means within a column (per year) followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.

Table 4. Gross margins for insect control programs at MSU2 for varying refuge requirements at a corn selling price of $100/Mg.

Year	WCR control program [a,b]	No refuge		10% refuge		20% refuge	
		-----------------------------$/ha		----------------------------------			
2004	*Bt*-hybrid (T)	1192	a	1189	a	1186	a
	SAI (C)	1161	ab	1161	ab	1161	ab
	SAI + LST(C)	1165	ab	1165	ab	1165	ab
	HST (C)	1146	b	1146	b	1146	b
	LSD(0.05) [c]	42		41		41	
2005	*Bt*-hybrid (T)	1176	a	1169	a	1163	a
	SAI (C)	1110	b	1110	ab	1110	ab
	SAI + LST (C)	1067	b	1067	b	1067	b
	HST (C)	903	c	903	c	903	c
	LSD(0.05)	64		64		63	
2006	*Bt*-hybrid (T)	1136	a	1108	a	1081	a
	SAI (C)	805	c	805	b	805	b
	SAI + LST (C)	1108	b	1108	a	1108	a
	HST (C)	1020	ab	1020	a	1020	a
	LSD(0.05)	123		122		122	

[a]Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[b]SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[c]Means within a column (per year) followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.

Table 5. Gross margins for insect control programs at MSU2 for varying refuge requirements at a corn selling price of $140/Mg.

Year	WCR control program [a,b]	No refuge		10% refuge		20% refuge	
		-----------------------------$/ha-----------------------------					
2004	*Bt*-hybrid (T)	1762	a	1758	a	1756	a
	SAI (C)	1730	a	1730	a	1730	a
	SAI + LST(C)	1742	a	1742	a	1742	a
	HST (C)	1708	a	1708	a	1708	a
	LSD(0.05) [c]	58		58		57	
2005	*Bt*-hybrid (T)	1742	a	1735	a	1728	a
	SAI (C)	1670	ab	1670	ab	1670	ab
	SAI + LST (C)	1608	b	1608	b	1608	b
	HST (C)	1371	c	1371	c	1371	c
	LSD(0.05)	89		88		88	
2006	*Bt*-hybrid (T)	1682	a	1645	a	1608	a
	SAI (C)	1229	b	1229	b	1229	b
	SAI + LST (C)	1521	a	1521	a	1521	a
	HST (C)	1530	a	1530	a	1530	a
	LSD(0.05)	172		172		171	

[a]Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[b]SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[c]Means within a column (per year) followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.

Table 6. Gross margins for insect control programs at MSU2 for varying refuge requirements at a corn selling price of $180/Mg.

Year	WCR control program [a,b]	No refuge		10% refuge		20% refuge	
		-----------------------------$/ha-----------------------------					
2004	*Bt*-hybrid (T)	2333	a	2329	a	2326	a
	SAI (C)	2300	a	2300	a	2300	a
	SAI + LST(C)	2319	a	2319	a	2319	a
	HST (C)	2269	a	2269	a	2269	a
	LSD(0.05)[c]	74		74		73	
2005	*Bt*-hybrid (T)	2309	a	2301	a	2293	a
	SAI (C)	2229	ab	2229	ab	2229	ab
	SAI + LST (C)	2149	b	2149	b	2149	b
	HST (C)	1838	c	1838	c	1838	c
	LSD(0.05)	115		113		112	
2006	*Bt*-hybrid (T)	2228	a	2182	a	2135	a
	SAI (C)	1653	b	1653	b	1653	b
	SAI + LST (C)	2034	a	2034	a	2034	a
	HST (C)	2040	a	2040	a	2040	a
	LSD(0.05)	222		221		221	

[a]Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[b]SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[c]Means within a column (per year) followed by the same letter are not significantly different (α = 0.05) according to Fisher's Protected LSD.

Table 7. Gross margins for insect control programs at MSU1 for varying refuge requirements at a corn selling price of \$60/Mg.

Year	WCR control program [a,b]	No refuge		10% refuge		20% refuge	
		-----------------------------\$/ha-----------------------------					
2004	*Bt*-hybrid (T)	688	a	685	a	683	a
	SAI (C)	662	a	662	a	662	a
	SAI + LST(C)	282	a	282	a	282	a
	HST (C)	677	a	677	a	677	a
	LSD(0.05)[c]	51		48		46	
2005	*Bt*-hybrid (T)	500	a	500	a	500	a
	SAI (C)	499	a	662	a	662	a
	SAI + LST (C)	464	a	282	a	282	a
	HST (C)	369	b	677	b	677	b
	LSD(0.05)	46		45		45	
2006	*Bt*-hybrid (T)	426	a	416	a	406	a
	SAI (C)	326	c	662	c	662	b
	SAI + LST (C)	362	bc	282	bc	282	a
	HST (C)	378	ab	677	ab	677	a
	LSD(0.05)	49		49		49	

[a]Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[b]SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[c]Means within a column (per year) followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.

Table 8. Gross margins for insect control programs at MSU1 for varying refuge requirements at a corn selling price of $100/Mg.

Year	WCR control program [a,b]	No refuge		10% refuge		20% refuge	
		$/ha					
2004	*Bt*-hybrid (T)	1300	a	1297	a	1295	a
	SAI (C)	1276	a	1276	a	1276	a
	SAI + LST(C)	1320	a	1320	a	1320	a
	HST (C)	1297	a	1297	a	1297	a
	LSD(0.05) [c]	84		80		77	
2005	*Bt*-hybrid (T)	989	a	991	a	992	a
	SAI (C)	1007	a	1007	a	1007	a
	SAI + LST (C)	960	a	960	a	960	a
	HST (C)	787	b	787	b	787	b
	LSD(0.05)	76		75		74	
2006	*Bt*-hybrid (T)	864	a	849	a	835	a
	SAI (C)	718	b	718	b	718	b
	SAI + LST (C)	789	ab	789	ab	789	ab
	HST (C)	800	a	800	a	800	a
	LSD(0.05)	83		82		82	

[a]Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[b]SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[c]Means within a column (per year) followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.

Table 9. Gross margins for insect control programs at MSU1 for varying refuge requirements at a corn selling price of \$140/Mg.

Year	WCR control program [a,b]	No refuge		10% refuge		20% refuge	
		--------------------------\$/ha--------------------------------					
2004	*Bt*-hybrid (T)	1911	a	1909	a	1907	a
	SAI (C)	1890	a	1890	a	1890	a
	SAI + LST(C)	1957	a	1957	a	1957	a
	HST (C)	1918	a	1918	a	1918	a
	LSD(0.05) [c]	118		112		108	
2005	*Bt*-hybrid (T)	1478	a	1481	a	1485	a
	SAI (C)	1515	a	1515	a	1515	a
	SAI + LST (C)	1455	a	1455	a	1455	a
	HST (C)	1206	b	1206	b	1206	b
	LSD(0.05)	105		104		103	
2006	*Bt*-hybrid (T)	1302	a	1283	a	1263	a
	SAI (C)	1109	b	1109	b	1109	b
	SAI + LST (C)	1213	ab	1213	ab	1213	ab
	HST (C)	1223	ab	1223	ab	1223	ab
	LSD(0.05)	117		116		115	

[a]Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[b]SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[c]Means within a column (per year) followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.

Table 10. Gross margins for insect control programs at MSU1 for varying refuge requirements at a corn selling price of $180/Mg.

Year	WCR control program [a,b]	No refuge		10% refuge		20% refuge	
		--------------------------$/ha--------------------------------					
2004	*Bt*-hybrid (T)	2523	a	2521	a	2519	a
	SAI (C)	2504	a	2504	a	2504	a
	SAI + LST(C)	2595	a	2595	a	2595	a
	HST (C)	2538	a	2538	a	2538	a
	LSD(0.05)[c]	151		144		139	
2005	*Bt*-hybrid (T)	1967	a	1973	a	1978	a
	SAI (C)	2023	a	2023	a	2023	a
	SAI + LST (C)	1950	a	1950	a	1950	a
	HST (C)	1624	b	1624	b	1624	b
	LSD(0.05)	136		134		133	
2006	*Bt*-hybrid (T)	1740	a	1716	a	1692	a
	SAI (C)	1500	b	1500	b	1500	b
	SAI + LST (C)	1639	ab	1639	ab	1639	ab
	HST (C)	1646	ab	1646	ab	1646	ab
	LSD(0.05)	151		149		149	

[a]Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[b]SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[c]Means within a column (per year) followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.

Table 11. Gross margins for insect control programs at Mason/Eaton Rapids for varying refuge requirements at a corn selling price of $60/Mg.

Year	WCR control program [a,b]	No refuge		10% refuge		20% refuge	
		$/ha					
2004	*Bt*-hybrid (T)	405	a	400	a	394	a
	SAI (C)	350	b	350	a	350	a
	SAI + LST(C)	356	ab	356	a	356	a
	HST (C)	361	ab	361	a	361	a
	LSD(0.05)[c]	55		54		49	
2005	*Bt*-hybrid (T)	433	a	429	a	425	a
	SAI (C)	393	ab	393	ab	393	ab
	SAI + LST (C)	351	b	351	b	351	bc
	HST (C)	325	b	325	b	325	c
	LSD(0.05)	70		69		64	
2006	*Bt*-hybrid (T)	386	a	373	a	360	a
	SAI (C)	344	a	344	a	344	a
	SAI + LST (C)	317	a	317	a	317	a
	HST (C)	329	a	329	a	329	a
	LSD(0.05)	101		96		88	

[a]Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[b]SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[c]Means within a column (per year) followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.

Table 12. Gross margins for insect control programs at Mason/Eaton Rapids for varying refuge requirements at a corn selling price of $100/Mg.

Year	WCR control program [a,b]	No refuge		10% refuge		20% refuge	
		---------------------------$/ha---------------------------					
2004	*Bt*-hybrid (T)	829	a	821	a	814	a
	SAI (C)	755	a	755	a	755	a
	SAI + LST(C)	777	a	777	a	777	a
	HST (C)	770	a	770	a	770	a
	LSD(0.05)[c]	89		88		87	
2005	*Bt*-hybrid (T)	878	a	873	a	868	a
	SAI (C)	831	a	831	a	831	a
	SAI + LST (C)	771	ab	771	ab	771	ab
	HST (C)	714	b	714	b	714	b
	LSD(0.05)	115		114		113	
2006	*Bt*-hybrid (T)	799	a	779	a	759	a
	SAI (C)	752	a	752	a	752	a
	SAI + LST (C)	714	a	714	a	714	a
	HST (C)	720	a	720	a	720	a
	LSD(0.05)	171		163		157	

[a]Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[b]SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[c]Means within a column (per year) followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.

Table 13. Gross margins for insect control programs at Mason/Eaton Rapids for varying refuge requirements at a corn selling price of $140/Mg.

Year	WCR control program [a,b]	No refuge		10% refuge		20% refuge	
		-----------------------------$/ha-----------------------------					
2004	*Bt*-hybrid (T)	1252	a	1243	a	1234	a
	SAI (C)	1161	a		a		a
	SAI + LST(C)	1198	a		a		a
	HST (C)	1180	a		a		a
	LSD(0.05)[c]	120		122		121	
2005	*Bt*-hybrid (T)	1322	a	1317	a	1312	a
	SAI (C)	1269	a		a		a
	SAI + LST (C)	1192	ab		ab		ab
	HST (C)	1103	b		b		b
	LSD(0.05)	161		160		158	
2006	*Bt*-hybrid (T)	1212	a	1185	a	1158	a
	SAI (C)	1160	a		a		a
	SAI + LST (C)	1111	a		a		a
	HST (C)	1110	a		a		a
	LSD(0.05)	241		231		221	

[a]Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.
[b]SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.
[c]Means within a column (per year) followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.

Table 14. Gross margins for insect control programs at Mason/Eaton Rapids for varying refuge requirements at a corn selling price of $180/Mg.

Year	WCR control program [a,b]	No refuge		10% refuge		20% refuge	
		--------------------------$/ha--------------------------------					
2004	*Bt*-hybrid (T)	1675	a	1664	a	1653	a
	SAI (C)	1566	a	1566	a	1566	a
	SAI + LST(C)	1619	a	1619	a	1619	a
	HST (C)	1589	a	1589	a	1589	a
	LSD(0.05)[c]	159		156		155	
2005	*Bt*-hybrid (T)	1767	a	1761	a	1755	a
	SAI (C)	1707	a	1707	a	1707	a
	SAI + LST (C)	1613	ab	1613	ab	1613	ab
	HST (C)	1492	b	1492	b	1492	b
	LSD(0.05)	202		205		203	
2006	*Bt*-hybrid (T)	1624	a	1591	a	1557	a
	SAI (C)	1568	a	1568	a	1568	a
	SAI + LST (C)	1507	a	1507	a	1507	a
	HST (C)	1501	a	1501	a	1501	a
	LSD(0.05)	312		298		286	

[a]Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[b]SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[c]Means within a column (per year) followed by the same letter are not significantly different (α = 0.05) according to Fisher's Protected LSD.

Table 15. Gross margins for insect control programs at Westphalia for varying refuge requirements at a corn selling price of $60/Mg.

Year	WCR control program [a,b]	No refuge		10% refuge		20% refuge	
		-----------------------------$/ha-----------------------------					
2004	*Bt*-hybrid (T)	378	a	375	a	372	a
	SAI (C)	345	a	345	a	345	a
	SAI + LST(C)	331	a	331	a	331	a
	HST (C)	356	a	356	a	356	a
	LSD(0.05)[c]	52		52		51	
2005	*Bt*-hybrid (T)	368	a	354	a	340	a
	SAI (C)	229	b	229	b	229	b
	SAI + LST (C)	235	b	235	b	235	b
	HST (C)	185	c	185	c	185	c
	LSD(0.05)	43		42		41	
2006	*Bt*-hybrid (T)	464	a	453	a	441	a
	SAI (C)	350	bc	350	bc	350	bc
	SAI + LST (C)	370	b	370	b	370	b
	HST (C)	291	c	291	c	291	c
	LSD(0.05)	62		61		60	

[a]Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[b]SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[c]Means within a column (per year) followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.

Table 16. Gross margins for insect control programs at Westphalia for varying refuge requirements at a corn selling price of $100/Mg.

Year	WCR control program [a,b]	No refuge		10% refuge		20% refuge	
		$/ha					
2004	*Bt*-hybrid (T)	788	a	784	a	781	a
	SAI (C)	751	a	751	a	751	a
	SAI + LST(C)	739	a	739	a	739	a
	HST (C)	768	a	768	a	768	a
	LSD(0.05) [c]	84		83		83	
2005	*Bt*-hybrid (T)	769	a	748	a	727	a
	SAI (C)	556	b	556	b	556	b
	SAI + LST (C)	578	b	578	b	578	b
	HST (C)	481	c	481	c	481	c
	LSD(0.05)	72		70		69	
2006	*Bt*-hybrid (T)	929	a	912	a	895	a
	SAI (C)	759	bc	759	b	759	ab
	SAI + LST (C)	802	b	802	b	802	b
	HST (C)	657	c	657	c	657	c
	LSD(0.05)	103		101		99	

[a]Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[b]SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[c]Means within a column (per year) followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.

Table 17. Gross margins for insect control programs at Westphalia for varying refuge requirements at a corn selling price of $140/Mg.

Year	WCR control program [a,b]	No refuge		10% refuge		20% refuge	
		-------------	-------------	$/ha	-------------	-------------	
2004	*Bt*-hybrid (T)	1198	a	1194	a	1190	a
	SAI (C)	1158	a	1158	a	1158	a
	SAI + LST(C)	1148	a	1148	a	1148	a
	HST (C)	1179	a	1179	a	1179	a
	LSD(0.05)[c]	117		116		115	
2005	*Bt*-hybrid (T)	1171	a	1142	a	1114	a
	SAI (C)	884	b	884	b	884	b
	SAI + LST (C)	921	b	921	b	921	b
	HST (C)	776	c	776	c	776	c
	LSD(0.05)	101		99		96	
2006	*Bt*-hybrid (T)	1395	a	1372	a	1350	a
	SAI (C)	1168	b	1168	b	1168	b
	SAI + LST (C)	1235	b	1235	ab	1235	ab
	HST (C)	1023	c	1023	c	1023	c
	LSD(0.05)	144		141		138	

[a]Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[b]SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[c]Means within a column (per year) followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.

Table 18. Gross margins for insect control programs at Westphalia for varying refuge requirements at a corn selling price of $180/Mg.

Year	WCR control program [a,b]	No refuge		10% refuge		20% refuge	
		-----------------------------$/ha		--------------------------------			
2004	*Bt*-hybrid (T)	1608	a	1603	a	1599	a
	SAI (C)	1565	a	1565	a	1565	a
	SAI + LST(C)	1556	a	1556	a	1556	a
	HST (C)	1591	a	1591	a	1591	a
	LSD(0.05)[c]	149		148		147	
2005	*Bt*-hybrid (T)	1572	a	1536	a	1500	a
	SAI (C)	1212	b	1212	b	1212	b
	SAI + LST (C)	1263	b	1263	b	1263	b
	HST (C)	1072	c	1072	c	1072	c
	LSD(0.05)	130		127		124	
2006	*Bt*-hybrid (T)	1860	a	1832	a	1804	a
	SAI (C)	1577	b	1577	b	1577	b
	SAI + LST (C)	1668	b	1668	ab	1668	ab
	HST (C)	1390	c	1390	c	1390	c
	LSD(0.05)	186		181		177	

[a]Abbreviations: SAI, soil-applied insecticide; LST, low seed treatment; HST, high seed treatment; T, denotes a transgenic *Bt* corn program for insect control; C, denotes a conventional insecticide program.

[b]SAI was tefluthrin applied at planting; LST is a commercial seed coating of cothianidin at 0.25 mg a.i./kernel; HST is a commercial seed coating of clothianidin at 1.25 mg a.i./kernel.

[c]Means within a column (per year) followed by the same letter are not significantly different ($\alpha = 0.05$) according to Fisher's Protected LSD.