FACULTY PAPER SERIES

FP 02-04 May 2002

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Abstract

Data from field experiments are used to estimate the yield benefit of corn hybrids containing event MON 863 relative to nontransgenic corn hybrids without corn rootworm control and with a soil insecticide for corn rootworm control. Over typical ranges for corn rootworm population pressure, event MON 863 provides a yield benefit of 9-28% relative to no control and of 1.5-4.5% relative to control with a soil insecticide. For a reasonable range of prices and yields, the value of the event MON 863 yield benefit is $25-$75/ac relative to no control and $4-$12/ac relative to control with a soil insecticide, depending on corn rootworm pressure.

Because of the low correlation between yield loss and the root rating difference, a common empirical finding when estimating yield loss with root ratings, the 95% confidence intervals around these averages are quite wide. Though on average, event MON 863 has substantial value, the wide confidence intervals imply that farmers will see a wide variety of actual performance levels in their fields. This uncertainty in the realized yield benefit is not due to any property of event MON 863, but rather due to the inherent randomness in the numerous environmental and agronomic factors determining a corn plant's yield and yield response to corn rootworm larval feeding damage.

Introduction

This report estimates the yield benefit of corn hybrids containing event MON 863, the new transgenic corn event developed by Monsanto that provides control of western and northern corn rootworm larvae. The yield benefit of event MON 863 is estimated relative to no corn rootworm control and relative to control with a soil insecticide. This analysis is not a full accounting of the benefits of hybrids containing event MON 863, only the yield benefit. Event MON 863 provides other benefits to farmers and to society that this analysis does not include. For example, most farmers adopting hybrids containing event MON 863 will reduce insecticide use, but the human health and environmental benefits to farmers and society of this decrease are not included.

As is typical early in the product development process for transgenic corn events, initial field evaluations were conducted with the transgenic event in non-elite hybrids. As a result, no yield data were collected, since such data would not be indicative of actual yield performance of the event in elite hybrids. Rather, field performance was measured by the standard 1-6 root rating scale of Hills and Peters (1971). Field data from Gray and Steffey (1998) are used to estimate proportional yield loss as a function of the root rating difference. Applying this model to data from field trials with hybrids containing event MON 863 provides an estimate of the yield benefit of event MON 863 relative to no corn rootworm control and relative to control with a soil insecticide.

Data used for Estimations

Gray and Steffey (1998) Data

Three years (1994-1996) of data from experiments conducted by Gray and Steffey (1998) in 2 locations in Illinois (near Urbana and DeKalb) were used for this analysis.

Whole plot treatments were 12 commonly grown nontransgenic maize hybrids. Sub-plot treatments were 2 rows treated with terbufos (Counter 15G) and 2 untreated rows. Depending on the year and location, 8-10 replicates for each hybrid were planted. Collected data included machine-harvested yield and the average root rating for five plants on the 1-6 scale of Hills and Peters (1971). Only data with treated and untreated yields and root ratings for both sub-plots were used, so that both the root rating difference and proportional yield loss could be calculated. The final result was 621 observations of yield (bu/ac) and average root rating for the paired untreated and soil insecticide treated sub-plots. For a more complete description, see Gray and Steffey (1998).

Tables 1 and 2 summarize the data. The root rating difference ΔR is calculated as

(1) $$\Delta R = \left| R_N - R_S \right| .$$

R_N is the average root rating for the untreated sub-plot and R_S is the average root rating for the soil insecticide sub-plot. When $R_N > R_S$, proportional yield loss λ is calculated as

(2) $$\lambda = (Y_S - Y_N) / Y_S ,$$

where Y_N is the yield for the untreated sub-plot and Y_S is the yield for the soil insecticide sub-plot. So that proportional yield loss is relative to yield from the plot with the lowest root rating, for the nine instances when $R_S > R_N$, proportional yield loss is calculated as

(3) $$\lambda = (Y_N - Y_S) / Y_N .$$

Gray and Steffey (1998) report statistically significant differences in yields and root ratings for some site-years. However, a model with site-year effects is not appropriate for the analysis here, since the type of site-year that will occur is in general unknown. As a result, the data are pooled to estimate a function that averages across years and locations to determine average yield loss given the root rating difference.

Monsanto Event MON 863 Efficacy Data

Data from efficacy experiments conducted in 1999 and 2000 in several locations were used to estimate the impact of event MON 863 on the root rating. Monsanto (2000) and Pilcher (2001) describe the experiments and report the average root rating for each treatment at each location. Plots were artificially infested or had a trap crop planted the previous season to ensure high western corn rootworm larval populations. Table 3 reports all the data used for this analysis.

Model

Proportional Yield Loss as a Function of the Root Rating Difference

Several factors contribute to any observed yield difference between an untreated plot and a treated plot. Soil characteristics vary, tillage and nutrient applications are not uniform, yields are measured with error, and experimental treatments are applied with error. As a result, yield variability due to soil heterogeneity, non-uniformity of tillage, nutrient and pesticide applications, and yield measurement error is confounded with yield variability due to the treatment. A statistical model is needed that separates the treatment effect on yield from the effect of the other "noise" factors.

The composed error model of Mitchell, Gray and Steffey (2002) separates proportional yield loss into (1) a mean-zero normal error to capture yield variability due to soil heterogeneity, non-uniformity of agronomic practices, measurement errors, and similar factors and (2) a strictly positive error to capture yield loss due to corn rootworm damage. Specifically, the model assumes proportional yield loss λ is composed of two independent errors—a normal (Gaussian) error ε and a strictly positive error δ:

(4) $$\lambda = 1 - \exp(-(\delta + \varepsilon)).$$

The normal error ε has a zero mean and variance σ^2, while δ has an exponential distribution with mean θ. When the untreated yield is zero, $\lambda = 1$ (a 100% loss) by equation (2). When the yield with soil insecticide is zero, $\lambda = -\infty$ by equation (2). Equation (4) imposes these same limits on λ.

Maximum likelihood is used to estimate the parameters of the probability density function for λ, conditional on the root rating difference. The mean of this conditional distribution is the average proportional yield loss as a function of the root rating difference. The same six conditional models estimated by Mitchell, Gray and Steffey (2002) were estimated with these data. Table 4 reports the results. The analysis here uses the linear model because it provides the best fit as measured by the adjusted R^2 and the root mean square error (RMSE), and is parsimonious in terms of the number of parameters. Figure 1 illustrates the model fit.

None of the models provides a high adjusted R^2 or a low RMSE. As Figure 1 shows, proportional yield loss varies substantially when the root rating differences is constant. As a result, a low correlation between proportional yield loss and the root rating difference exists ($\rho = 0.44$) and a low adjusted R^2 occurs. The positive relationship between root rating and yield loss is well established in the literature (Turpin et al. 1972, Stamm et al. 1985, Sutter et al. 1990, Davis 1994, Urias-Lopez and Meinke 2001), though empirically a low correlation is common. Even under equal agronomic treatment, corn yields are highly variable within a field. The low correlation between root ratings and yield loss occurs because numerous environmental and agronomic factors together determine a corn plant's yield and yield response to root damage.

The purged form of the conditional model is appropriate for the analysis here, since the focus is on the impact of corn rootworm control on yield, not the effect of soil heterogeneity and similar factors. As such, the probability density function for λ is

(5) $$h(\lambda) = \left((1-\lambda)^{\frac{1-\theta}{\theta}} \right) / \theta$$

for $0 \le \lambda \le 1$, and 0 otherwise, and the cumulative distribution function is

(6) $$H(\lambda) = 1 - (1-\lambda)^{1/\theta},$$

where $\theta = \alpha\Delta R/(1-\alpha\Delta R)$. Mean loss is $\mu_\lambda = \alpha\Delta R$. Using the estimated α reported in Table 4 for the linear model, average proportional loss given the root rating difference is

(7) $$\mu_\lambda = 0.125\Delta R$$

and $\theta = 0.125\Delta R/(1-0.125\Delta R)$. Inverting the cumulative distribution function gives the lower and upper limits of the 95% confidence interval for the purged model:

(8) $$\lambda_{lower} = 1 - (1-0.025)^{\theta},$$

(9) $$\lambda_{upper} = 1 - (1-0.975)^{\theta}.$$

On average, over many years and across many locations, Figure 1 shows that the average yield benefit can be quite substantial, depending on the corn rootworm pressure as measured by the untreated root rating. However, Figure 1 also shows that, though on average the yield benefit is substantial, the actual yield benefit realized by a farmer in a particular field for a particular year can easily vary between 0% to almost 100%. As a result, at an aggregate level, such as at a county, state or regional level, soil insecticides on average save a substantial amount of yield, but for an individual farmer, the realized benefit on a specific field during any particular year is quite variable. This uncertainty in the realized benefit results from the inherent uncertainty in the environmental and agronomic factors that determine a corn plant's yield and yield response to root damage.

Soil Insecticide Root Rating as a Function of the Untreated Root Rating

The root rating data from Gray and Steffey (1998) are used to estimate the average root rating for corn treated with a soil insecticide as a function of the untreated root rating, i.e. the root rating for corn receiving no corn rootworm control. Because the root rating is strictly between 1 and 6, ordinary least squares regression is inappropriate, since the assumed normal error ranges between $-\infty$ and $+\infty$. The beta distribution has lower and upper limits like the root rating, and its flexibility make it a good choice for estimating a conditional root rating distribution via maximum likelihood.

Observed root ratings are first rescaled to range between 0 and 1 (the lower and upper limits of the standard beta density) by the following transformation:

(10) $$\widetilde{R} = (R-1)/(6-1),$$

where R is any root rating on the 1 to 6 scale and $\widetilde{R}$ is the re-scaled root rating between 0 and 1. The standard beta probability density function with parameters ν and γ has mean $\nu/(\nu+\gamma)$ and standard deviation $\sqrt{\nu\gamma/[(\nu+\gamma)^2(\nu+\gamma+1)]}$ (Evans et al. 1993).

This analysis assumes the conditional probability density function for the rescaled soil insecticide root rating $\widetilde{R}_S$ is beta with linear mean $\beta_S\widetilde{R}_N$ and constant standard deviation σ_S. Equating these to the mean and standard deviation formulas for the standard beta density gives two simultaneous equations that can be solved to obtain $\nu = \frac{(\beta_S\widetilde{R}_N)^2(1-\beta_S\widetilde{R}_N)-\beta_S\widetilde{R}_N\sigma_S^2}{\sigma_S^2}$ and $\gamma = \frac{(\beta_S\widetilde{R}_N)(1-\beta_S\widetilde{R}_N)^2-(1-\beta_S\widetilde{R}_N)\sigma_S^2}{\sigma_S^2}$ (Evans et al. 1993). Substituting these into the beta probability density function gives the density function of the rescaled root rating $\widetilde{R}_S$ conditional on the observed $\widetilde{R}_N$, which allows maximum likelihood estimation of the parameters β_S and σ_S as reported in Table 5.

Using estimated parameters and transforming back to the 1 to 6 scale, the average root rating for soil insecticide corn treated as a function of the untreated root rating is

(11) $$R_S = 1 + \beta_S (R_N - 1).$$

Using this conditional mean for the model prediction gives a RMSE of 0.392. Figure 2 illustrates the model fit.

Event MON 863 Root Rating as a Function of the Untreated Root Rating

Repeating the process used to obtain equation (11), but with the efficacy data in Table 3, gives the event MON 863 root rating as a function of the untreated root rating. Table 5 reports maximum likelihood parameter estimates for β_M and σ_M. Given these,

(12) $$R_M = 1 + \beta_M (R_N - 1),$$

where R_M is the average root rating for event MON 863. Using this conditional mean for the model prediction gives a RMSE of 0.390. Figure 3 illustrates the model fit.

Untreated Root Ratings

Equations (11) and (12) indicate that the untreated root rating is needed to obtain ΔR and then to use equation (7) to determine the average proportional yield loss. Unfortunately, few data concerning the untreated root rating for naturally infested corn are available. Most field experiments evaluating soil insecticides or other control methods plant a trap crop the previous season or use artificial infestation to ensure a high corn rootworm larval population. However, published literature provides some indication of untreated root ratings with and without trap crops.

Table 6 summarizes average root ratings for untreated plots for the Gray and Steffey (1998) experiments, which used a trap crop. The overall average of the averages is 4.11, but the averages range between 2.84 and 5.19. Table 7 summarizes results from soil insecticide trials conducted by Iowa State University Department of Entomology (1998, 1999), which used a trap crop. The overall average of the average root rating for untreated plots across all locations and years is 4.1, but the averages range between 2.2 and 5.2. Table 8, adapted from Table 1 in O'Neil et al. (2001), reports annual average root ratings for several untreated first-year fields in seven counties in east central Illinois for 1996-1999. The average of the averages is 2.68 and indicates the typical pressure from rotation resistant western corn rootworm laying eggs in soybeans.

Because of the limited data concerning typical untreated root ratings, the analysis here examines the yield benefit of event MON 863 over the full range of untreated root ratings, using the untreated root rating as an index of corn rootworm pressure. The trap crop data indicate that high corn rootworm pressure in these areas implies an untreated root rating of about 4.1. Data from O'Neil et al. (2000) indicate that for rotation resistant corn rootworm, the untreated root rating averages about 2.7. As a result, this analysis uses an untreated root rating of 2 for low corn rootworm pressure, 3 for moderate pressure, and 4 for high pressure. However, equations and plots are provided for determining the yield benefit for any untreated root rating.

Model Summary

Equation (7) determines average proportional yield loss as a function of the root rating difference. Equations (11) and (12) determine the root rating for soil insecticide treated corn and event MON 863 corn as a function of the untreated root rating. Substituting in estimated parameters, equations (11) and (12) can be used to determine the difference in the various root ratings as a function of the untreated root rating:

(13) $$\Delta R_{N,S} = R_N - R_S = (1-\beta_S)(R_N - 1) = 0.641(R_N - 1)$$

(14) $$\Delta R_{N,M} = R_N - R_M = (1-\beta_M)(R_N - 1) = 0.754(R_N - 1)$$

(15) $$\Delta R_{S,M} = R_S - R_M = (\beta_S - \beta_M)(R_N - 1) = 0.113(R_N - 1)\,.$$

Combining these equations with equation (7) gives the following equations:

(16) $$\lambda_{N,S} = 0.125\Delta R_{N,S} = 0.080(R_N - 1)$$

(17) $$\lambda_{N,M} = 0.125\Delta R_{N,M} = 0.094(R_N - 1)$$

(18) $$\lambda_{S,M} = 0.125\Delta R_{S,M} = 0.014(R_N - 1)\,.$$

Equations (16)-(18) determine the average yield benefit of corn rootworm control (measured as the proportion of yield saved) as a function of the corn rootworm pressure (measured by the untreated root rating). Equation (16) determines the average yield benefit of soil insecticide relative to no corn rootworm control, equation (17) determines the average yield benefit of event MON 863 relative to no corn rootworm control, and equation (18) determines the average yield benefit of event MON 863 relative to control with soil insecticide.

Equations (8) and (9) combined with equations (13)-(15) give the lower and upper limits of the 95% confidence interval. Because field plot data are used to estimate the yield benefit, this confidence interval is for the yield benefit at the individual field level, not at an aggregate level such as for a county, a state, or a region. The confidence interval at these more aggregated levels would be narrower because the yield benefit is averaged over a wider area.

Results

Yield Benefit of Event MON 863 Relative to No Corn Rootworm Control

Figure 4 and Table 9 summarize the average yield benefit for corn hybrids containing event MON 863, measured as the proportion of yield saved, relative to corn without rootworm control. The confidence interval indicates the large level of uncertainty concerning the realized yield benefit on a specific field during a particular season. This uncertainty does not result from any property of event MON 863, but rather is due to the inherent randomness in the numerous environmental and agronomic factors determining a corn plant's yield and yield response to corn rootworm larval feeding damage. At more aggregated levels such as the county, state or region, the average benefit would remain the same, but the confidence interval would be narrower because the area averaged over is larger.

The average yield benefit of event MON 863 relative to no corn rootworm control is quite substantial. At an untreated root rating of 3, the model predicts an average yield benefit of almost 19%. However, farmers are likely to see a wide variety of actual performance levels, since the confidence interval ranges approximately 0%-60%. As a result, though the average yield benefit is substantial, farmers are likely to discount the average yield benefit to adjust for this uncertainty in the yield benefit actually realized. Tables 9 and 10 indicate that the average yield benefit of event MON 863 relative to no corn rootworm control is similar in magnitude to the yield benefit for soil insecticide, and both have comparable confidence intervals. As a result, farmers will likely discount the average yield benefit of event MON 863 for this uncertainty at a level similar to what they currently discount the average yield benefit of a soil insecticide for the uncertainty in the yield benefit that it provides.

Yield Benefit of Event MON 863 Relative to Control with a Soil Insecticide

Figure 5 and Table 11 summarize the yield benefit for a hybrid containing event MON 863, measured as the proportion of yield saved, relative to using a soil insecticide for corn rootworm control. Again, the confidence interval indicates the uncertainty around this average yield benefit. Because the root rating difference between event MON 863 and a soil insecticide is smaller, the confidence interval is narrower. With an untreated root rating of 3, the average yield benefit is 2.8%, though likely to range between 0% and 10%.

Monetary Value of the Event MON 863 Yield Benefit

Because the yield benefit for a hybrid containing event MON 863 is given in terms of the proportion of yield saved, converting this benefit to a monetary value requires assuming a pest-free yield and price. Table 12 reports the monetary value of the event MON 863 yield benefit relative to no corn rootworm control reported in Table 9 for a variety of prices, yields, and untreated root ratings. With moderate corn rootworm pressure (an untreated root rating of 3), the average value of corn rootworm control with event MON 863 is around $50/ac for many farmers. Because of the linear relationship between the untreated root rating and the yield benefit, with low corn rootworm pressure (an untreated root rating of 2), the value is about $25/ac and with high corn rootworm pressure (an untreated root rating of 4), the value is about $75/ac. These values do not include the cost of a technology fee for use of event MON 863. Also, the wide confidence interval indicates the tremendous uncertainty in the actual value realized by a farmer. Because the uncertainty in the realized yield benefit for event MON 863 is similar in magnitude to the uncertainty in the yield benefit for a soil insecticide, farmers will likely discount the average value of event MON 863 for this uncertainty at a level similar to what they currently discount the average value of a soil insecticide.

Table 13 reports the value of the event MON 863 yield benefit relative to applying a soil insecticide for a variety of prices, yields, and untreated root ratings. Event MON 863 has greater value because it provides slightly better control. With moderate corn rootworm pressure (an untreated root rating of 3), event MON 863 on average provides a yield benefit worth about $8/ac. With low corn rootworm pressure (an untreated root rating of 2), the value is about $4/ac and with high corn rootworm pressure (an untreated root rating of 4), the value is about $12/ac. However, the confidence interval indicates that the value of the additional realized yield benefit likely ranges between $0-$40/ac, depending on the price, yield, and untreated root rating.

Summary

Data from Gray and Steffey (1998) and event MON 863 field trials were used to estimate the yield benefit for hybrids containing event MON 863 relative to corn without corn rootworm control and relative to corn receiving a soil insecticide. Over typical ranges for corn rootworm population pressure, event MON 863 provides a yield benefit of 9-28% relative to no control and of 1.5-4.5% relative to control with a soil insecticide.

For a reasonable range of prices and yields, the value of the event MON 863 yield benefit is \$25-\$75/ac relative to no control and \$4-\$12/ac relative to control with a soil insecticide, depending on corn rootworm pressure.

The field data used to develop these estimates indicate that a tremendous amount of variability in the yield benefit of event MON 863 exists. This uncertainty is not a property of event MON 863, but the of corn-insect agroecosystem in which many environmental and agronomic factors interact to determine a corn plant's yield and yield response to root damage. As a result, the 95% confidence intervals around the average yield benefits are quite wide. At an aggregate level of analysis, such as at the county, state or regional level, the estimated yield benefits remain the same, but the confidence intervals would be narrower. However, at the field level, these confidence intervals indicate the uncertainty a farmer faces concerning the realized yield benefit on a particular field for a particular year. As a result, farmers will discount these average values to account for this uncertainty.

These results require several qualifications. First, these values only refer to the yield benefit. No attempt is made to evaluate the other benefits of event MON 863. In addition, this analysis does not include any cost differences for the different corn rootworm control methods. Such adjustments are fairly easy to incorporate, since an event MON 863 technology fee is non-random. Furthermore, the analysis does not quantify the discount that farmers are likely to use to adjust the average yield benefit of event MON 863 to account for the uncertainty in the actual yield benefit realized.

The analysis also makes biological assumptions that may not be valid. The model was developed using data from soil insecticide experiments, then applied to event MON

863. This model assumes corn rootworm damage and the associated yield loss as measured by the root rating are equivalent for corn receiving a soil insecticide and corn containing event MON 863. Corn rootworm larval feeding behavior on the roots of hybrids containing event MON 863 may differ from corn treated with a soil insecticide, which could imply a different yield response by the corn plant. Thus, though the root ratings may be the same for corn receiving a soil insecticide and for corn containing event MON 863, the average yield benefit may differ. The model ignores this possibility, since no data were available. Once field trials are conducted with event MON 863 in elite hybrids and yield data are collected, this possibility can be investigated.

Similarly, this analysis ignores the possibility that hybrids containing event MON 863 provides more consistent control of corn rootworm larvae than soil insecticides. The model assumes that the yield benefit of event MON 863 is as uncertain as the yield benefit of a soil insecticide. However, soil insecticides are applied long before larval hatch, so that the realized level of efficacy depends on several random environmental factors. Hybrids containing event MON 863 should give more consistent control than a soil insecticide, since event MON 863 is a plant-incorporated insecticide, the insecticide is expressed in the root tissues at high concentrations during the period of larval feeding. Again, once field trials are conducted with event MON 863 in elite hybrids and yield data are collected, the potential for hybrids containing event MON 863 to provide more consistent control than soil insecticides can be investigated.

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Table 1. Summary of root rating difference data from Gray and Steffey (1998).

Location-Year	Average	Standard Deviation	Minimum	Maximum	n
DeKalb 1994	1.62	0.66	0.00	3.20	108
DeKalb 1995	0.90	0.62	0.00	2.60	117
DeKalb 1996	1.38	0.66	0.20	3.20	66
Urbana 1994	2.76	0.53	0.80	4.00	115
Urbana 1995	2.68	0.68	0.20	4.00	113
Urbana 1996	2.03	0.52	0.60	3.20	102
1994	2.21	0.82	0.00	4.00	223
1995	1.77	1.10	0.00	4.00	230
1996	1.78	0.66	0.20	3.20	168
DeKalb	1.28	0.71	0.00	3.20	291
Urbana	2.51	0.66	0.20	4.00	330
All sites-years	1.93	0.92	0.00	4.00	621

Table 2. Summary of proportional yield loss data from Gray and Steffey (1998).

Location-Year	Average	Standard Deviation	Minimum	Maximum	n	n < 0
DeKalb 1994	0.033	0.071	-0.210	0.197	108	31
DeKalb 1995	0.197	0.181	-0.436	0.501	117	14
DeKalb 1996	0.059	0.088	-0.112	0.288	66	16
Urbana 1994	0.272	0.157	-0.163	0.808	115	5
Urbana 1995	0.488	0.214	-0.363	0.850	113	2
Urbana 1996	0.197	0.110	-0.123	0.585	102	2
1994	0.156	0.17	-0.210	0.808	223	36
1995	0.340	0.25	-0.436	0.850	230	16
1996	0.143	0.12	-0.123	0.585	168	18
DeKalb	0.105	0.150	-0.436	0.501	291	61
Urbana	0.323	0.207	-0.363	0.850	330	9
All sites-years	0.221	0.212	-0.436	0.850	621	70

Table 3. Efficacy data from event MON 863 field trials.

Year	Location	Source	Average Root Rating by Treatment Control	MON 863	Force
1999	Monmouth, IL	a	3.78	1.70	2.38
1999	William, IA	a	3.95	1.82	2.45
1999	Atlantic, IA	a	4.08	1.93	2.48
1999	Brookings, SD	a	4.35	1.50	2.10
1999	Columbia, MO	a	4.44	1.86	2.55
1999	Tuscola, IL	a	4.98	1.00	2.15
1999	Thomasboro, IL	a	5.03	2.33	2.33
2000	Brownsburg, IN	b	4.04	2.04	2.04
2000	Aurora, NE	b	3.33	1.86	2.52
2000	Elwood, NE	b	3.83	1.92	3.33
2000	Gothemburg, NE	b	4.88	2.17	2.46
2000	North Liberty, IA	b	3.79	2.00	2.42
2000	Oxford, IN	b	3.08	2.00	2.00
2000	West Lafayette, IN	b	4.42	2.17	2.00
2000	Ames, IA	c	2.43	1.18	1.79
2000	Brookings, SD	c	5.23	1.08	2.53
2000	Franklin, IN	c	3.28	1.50	1.46
2000	Jerseyville, IL	c	3.12	1.89	2.32
2000	Monmouth, IL	c	2.54	1.26	1.22
2000	Stanton. MN	c	2.30	1.15	1.60
2000	Stromsburg, NE	c	3.82	1.34	2.59
2000	Thomasboro, IL	c	3.49	1.87	1.93
2000	Ames, IA	d	3.75	1.30	2.15
2000	Blacksburg, VA	d	2.35	2.25	2.00
2000	Clay Center, NE	d	4.35	2.20	2.65
2000	Concord, NE	d	4.05	2.20	2.20
2000	Lafayette, IN	d	2.35	1.08	1.85
2000	Mead, NE	d	2.90	1.25	1.75
2000	North Platte, NE	d	4.60	1.90	2.45
2000	Scottsbluff, NE	d	3.70	1.50	2.65
2000	Yuma, CO	d	4.28	1.80	2.93

[a] Monsanto (2000), Table 5.
[b] Pilcher (2001), Table 1.
[c] Pilcher (2001), Table 2.
[d] Pilcher (2001), Table 3.

Table 4. Estimated parameters (standard errors in parentheses) and goodness of fit measures for various corn rootworm damage functions.

Parameter	Linear	Quadratic	Cobb Douglas	Negative Exponential	Hyperbolic	Sigmoid
α	0.125	0.176	0.176	0.239	0.169	0.241
	(0.00368)	(0.00954)	(0.00789)	(0.00982)	(0.00683)	(0.0174)
β	--	-0.0242	0.346	2.0446	--	-0.0367
		(0.00357)	(0.0501)	(0.548)		(0.00661)
σ	0.015	0.0239	0.139	0.160	0.0222	0.135
	(0.00481)	(0.00911)	(0.0129)	(0.0137)	(0.00803)	(0.0232)
Adjusted R^2*	0.175	0.138	0.115	0.054	0.167	0.112
RMSE	0.193	0.197	0.199	0.206	0.194	0.200

* Since a zero intercept is imposed, the adjusted R^2 is appropriate, as opposed to the R^2.

Table 5. Maximum likelihood parameter estimates for the soil insecticide root rating and the event MON 863 root rating as functions of the untreated root rating.

Parameter	Estimate	Standard Error	p value
β_S	0.359	0.00442	< 0.001
σ_S	0.0713	0.00198	< 0.001
β_M	0.246	0.0336	< 0.001
σ_M	0.105	0.0155	< 0.001

Table 6. Average root ratings for untreated plots (with trap crops planted the previous season) for the Gray and Steffey (1998) data.

	------- Average Untreated Root Rating -------		
Year	DeKalb	Urbana	Both
1994	3.84	5.19	4.54
1995	2.84	4.88	3.84
1996	3.40	4.24	3.91
All	3.34	4.79	4.11

Table 7. Average root ratings for untreated plots (with trap crops planted the previous season) for Iowa State University Department of Entomology (1998, 1999) data.

	------- Average Untreated Root Rating -------		
Location	1998	1999	Both
Ames	5.0	4.9	5.0
Bryant	4.6	--	--
Cedar Rapids	4.1	5.2	4.7
Crawfordsville	3.9	4.0	4.0
Nashua	3.0	4.4	3.7
Sutherland	2.2	3.6	2.9
All Locations	3.8	4.4	4.1

Table 8. Average root ratings for untreated first-year fields in east-central Illinois from O'Neil et al. (2000), Table 1.

Year	Number of Fields	Average Untreated Root Rating
1996	14	2.25
1997	17	3.40
1998	15	2.82
1999	28	2.26
		Average 2.68

Table 9. Estimated average yield benefit for corn hybrids containing event MON 863 relative to no corn rootworm control.

------ Root Ratings ------			Average		
Untreated	MON 863	Change	Yield Benefit	Confidence Interval	
R_N	R_M	$\Delta R_{N,M}$	$\lambda_{N,M}$	Lower	Upper
1	1.00	0.00	0.0%	0.0%	0.0%
2	1.25	0.75	9.4%	0.3%	31.9%
3	1.49	1.51	18.8%	0.6%	57.5%
4	1.74	2.26	28.3%	1.0%	76.6%
5	1.98	3.02	37.7%	1.5%	89.2%
6	2.23	3.77	47.1%	2.2%	96.2%

Table 10. Estimated average yield benefit for control with a soil insecticide relative to no corn rootworm control.

------ Root Ratings ------			Average		
Untreated	Soil Insecticide	Change	Yield Benefit	Confidence Interval	
R_N	R_S	$\Delta R_{N,S}$	$\lambda_{N,S}$	Lower	Upper
1	1.00	0.00	0.0%	0.0%	0.0%
2	1.36	0.64	8.0%	0.2%	27.4%
3	1.72	1.28	16.0%	0.5%	50.5%
4	2.08	1.92	24.0%	0.8%	68.8%
5	2.44	2.56	32.0%	1.2%	82.4%
6	2.80	3.20	40.0%	1.7%	91.5%

Table 11. Estimated average yield benefit for corn hybrids containing event MON 863 relative to control with a soil insecticide.

------------- Root Ratings -------------				Average		
Untreated	Soil Insecticide	MON 863	Change	Yield Benefit	Confidence Interval	
R_N	R_S	R_M	$\Delta R_{S,M}$	$\lambda_{S,M}$	Lower	Upper
1	1.00	1.00	0.00	0.0%	0.0%	0.0%
2	1.36	1.25	0.11	1.4%	0.0%	5.2%
3	1.72	1.49	0.23	2.8%	0.1%	10.2%
4	2.08	1.74	0.34	4.2%	0.1%	15.1%
5	2.44	1.98	0.45	5.7%	0.2%	19.9%
6	2.80	2.23	0.57	7.1%	0.2%	24.5%

Table 12. Average value of the yield benefit for corn hybrids containing event MON 863 relative to no corn rootworm control, for a range of average yields and prices.

Average Yield	Average Price	Untreated Root Rating	Average Value ($/ac)	Confidence Interval Lower	Confidence Interval Upper
160	2.00	2	$ 30.14	$ 0.84	$ 101.93
160	2.00	3	$ 60.27	$ 1.87	$ 184.05
160	2.00	4	$ 90.41	$ 3.17	$ 245.13
160	2.15	2	$ 32.40	$ 0.90	$ 109.58
160	2.15	3	$ 64.79	$ 2.02	$ 197.85
160	2.15	4	$ 97.19	$ 3.41	$ 263.52
160	2.30	2	$ 34.66	$ 0.97	$ 117.22
160	2.30	3	$ 69.31	$ 2.16	$ 211.66
160	2.30	4	$ 103.97	$ 3.65	$ 281.90
140	2.00	2	$ 26.37	$ 0.74	$ 89.19
140	2.00	3	$ 52.74	$ 1.64	$ 161.04
140	2.00	4	$ 79.11	$ 2.78	$ 214.49
140	2.15	2	$ 28.35	$ 0.79	$ 95.88
140	2.15	3	$ 56.69	$ 1.76	$ 173.12
140	2.15	4	$ 85.04	$ 2.99	$ 230.58
140	2.30	2	$ 30.32	$ 0.85	$ 102.57
140	2.30	3	$ 60.65	$ 1.89	$ 185.20
140	2.30	4	$ 90.97	$ 3.19	$ 246.66
120	2.00	2	$ 22.60	$ 0.63	$ 76.45
120	2.00	3	$ 45.20	$ 1.41	$ 138.04
120	2.00	4	$ 67.81	$ 2.38	$ 183.85
120	2.15	2	$ 24.30	$ 0.68	$ 82.18
120	2.15	3	$ 48.59	$ 1.51	$ 148.39
120	2.15	4	$ 72.89	$ 2.56	$ 197.64
120	2.30	2	$ 25.99	$ 0.73	$ 87.92
120	2.30	3	$ 51.98	$ 1.62	$ 158.74
120	2.30	4	$ 77.98	$ 2.74	$ 211.43
100	2.00	2	$ 18.83	$ 0.53	$ 63.71
100	2.00	3	$ 37.67	$ 1.17	$ 115.03
100	2.00	4	$ 56.50	$ 1.98	$ 153.21
100	2.15	2	$ 20.25	$ 0.57	$ 68.49
100	2.15	3	$ 40.50	$ 1.26	$ 123.66
100	2.15	4	$ 60.74	$ 2.13	$ 164.70
100	2.30	2	$ 21.66	$ 0.60	$ 73.26
100	2.30	3	$ 43.32	$ 1.35	$ 132.29
100	2.30	4	$ 64.98	$ 2.28	$ 176.19

Table 13. Average value of the yield benefit for corn hybrids containing event MON 863 relative to control with a soil insecticide, for a range of average yields and prices.

Average Yield	Average Price	Untreated Root Rating	Value ($/ac)	Confidence Interval Lower	Confidence Interval Upper
160	2.00	2	$ 4.53	$0.12	$16.52
160	2.00	3	$ 9.06	$0.24	$32.63
160	2.00	4	$13.60	$0.36	$48.32
160	2.15	2	$ 4.87	$0.13	$17.76
160	2.15	3	$ 9.74	$0.25	$35.07
160	2.15	4	$14.62	$0.39	$51.95
160	2.30	2	$ 5.21	$0.13	$19.00
160	2.30	3	$10.42	$0.27	$37.52
160	2.30	4	$15.64	$0.41	$55.57
140	2.00	2	$ 3.97	$0.10	$14.45
140	2.00	3	$ 7.93	$0.21	$28.55
140	2.00	4	$11.90	$0.31	$42.28
140	2.15	2	$ 4.26	$0.11	$15.54
140	2.15	3	$ 8.53	$0.22	$30.69
140	2.15	4	$12.79	$0.34	$45.45
140	2.30	2	$ 4.56	$0.12	$16.62
140	2.30	3	$ 9.12	$0.24	$32.83
140	2.30	4	$13.68	$0.36	$48.62
120	2.00	2	$ 3.40	$0.09	$12.39
120	2.00	3	$ 6.80	$0.18	$24.47
120	2.00	4	$10.20	$0.27	$36.24
120	2.15	2	$ 3.65	$0.09	$13.32
120	2.15	3	$ 7.31	$0.19	$26.31
120	2.15	4	$10.96	$0.29	$38.96
120	2.30	2	$ 3.91	$0.10	$14.25
120	2.30	3	$ 7.82	$0.20	$28.14
120	2.30	4	$11.73	$0.31	$41.68
100	2.00	2	$ 2.83	$0.07	$10.32
100	2.00	3	$ 5.67	$0.15	$20.39
100	2.00	4	$ 8.50	$0.22	$30.20
100	2.15	2	$ 3.05	$0.08	$11.10
100	2.15	3	$ 6.09	$0.16	$21.92
100	2.15	4	$ 9.14	$0.24	$32.47
100	2.30	2	$ 3.26	$0.08	$11.87
100	2.30	3	$ 6.52	$0.17	$23.45
100	2.30	4	$ 9.77	$0.26	$34.73

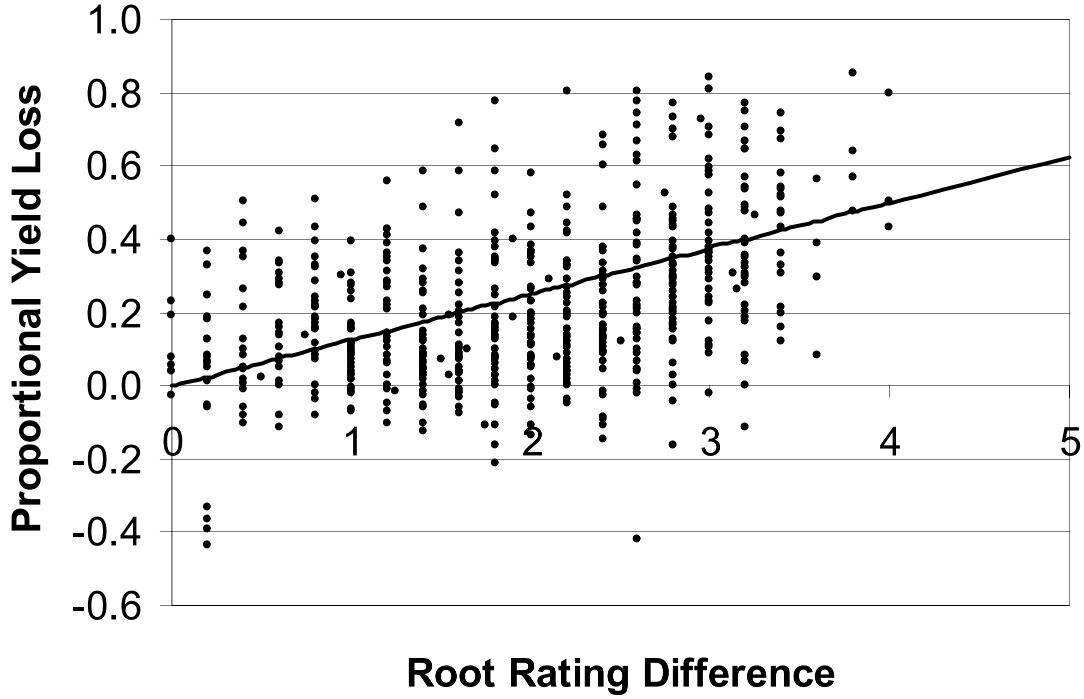

Figure 1. Observed proportional yield loss and predicted mean as a function of the root rating difference.

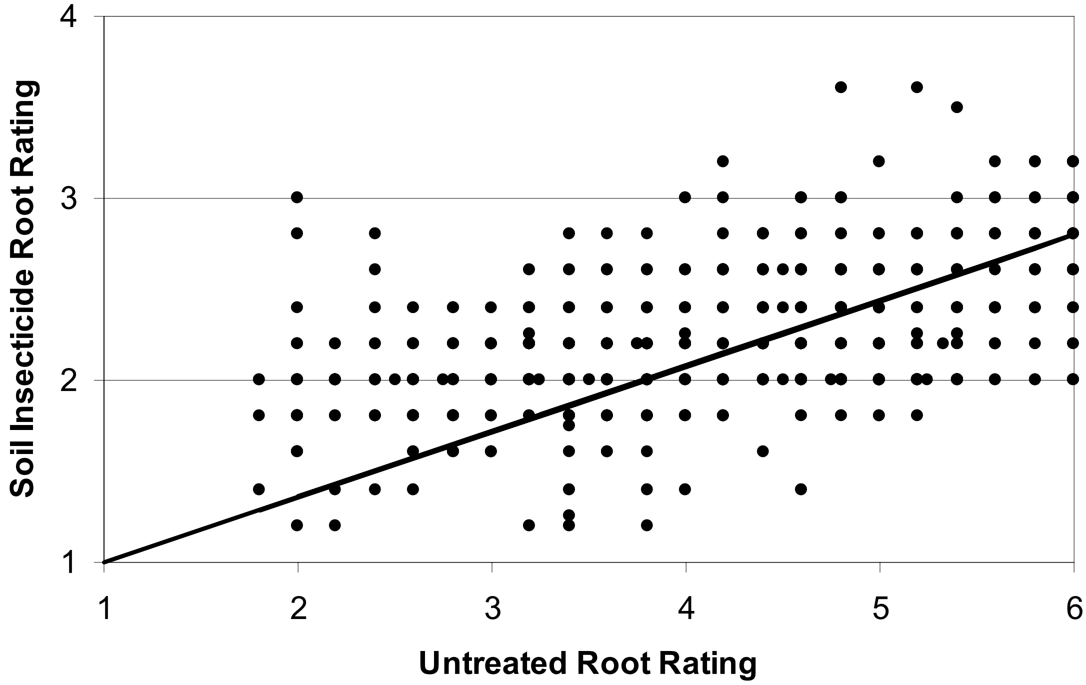

Figure 2. Observed and predicted soil insecticide root rating as a function of the untreated root rating using Gray and Steffey (1998) data.

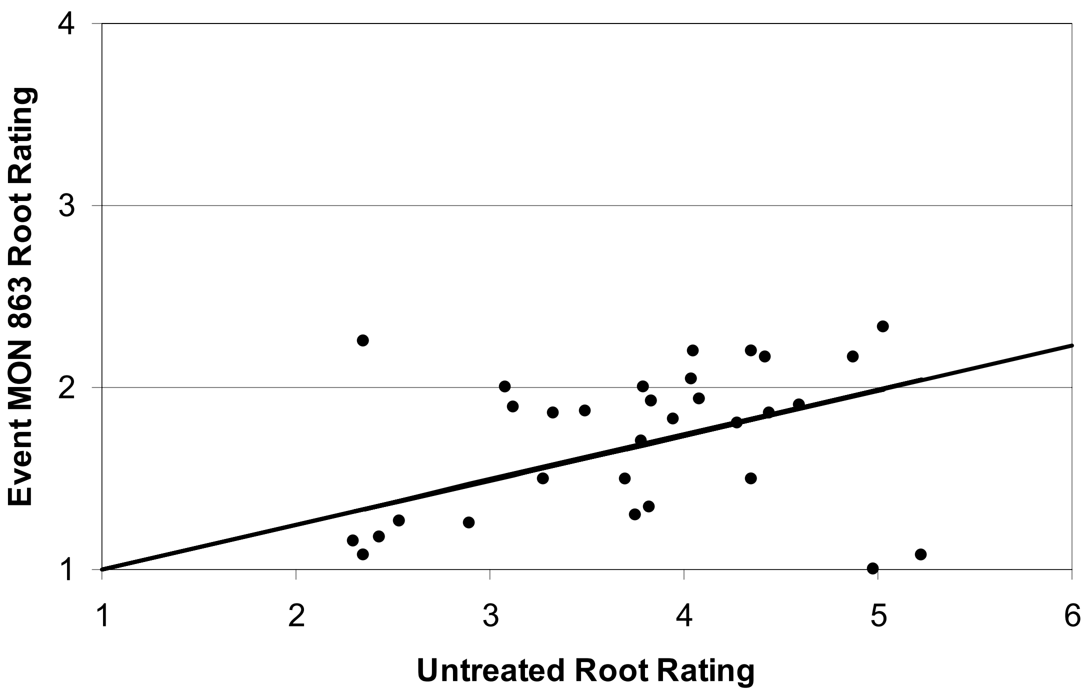

Figure 3. Observed and predicted event MON 863 root rating as a function of the untreated root rating using Monsanto (2000) and Pilcher (2001) data.

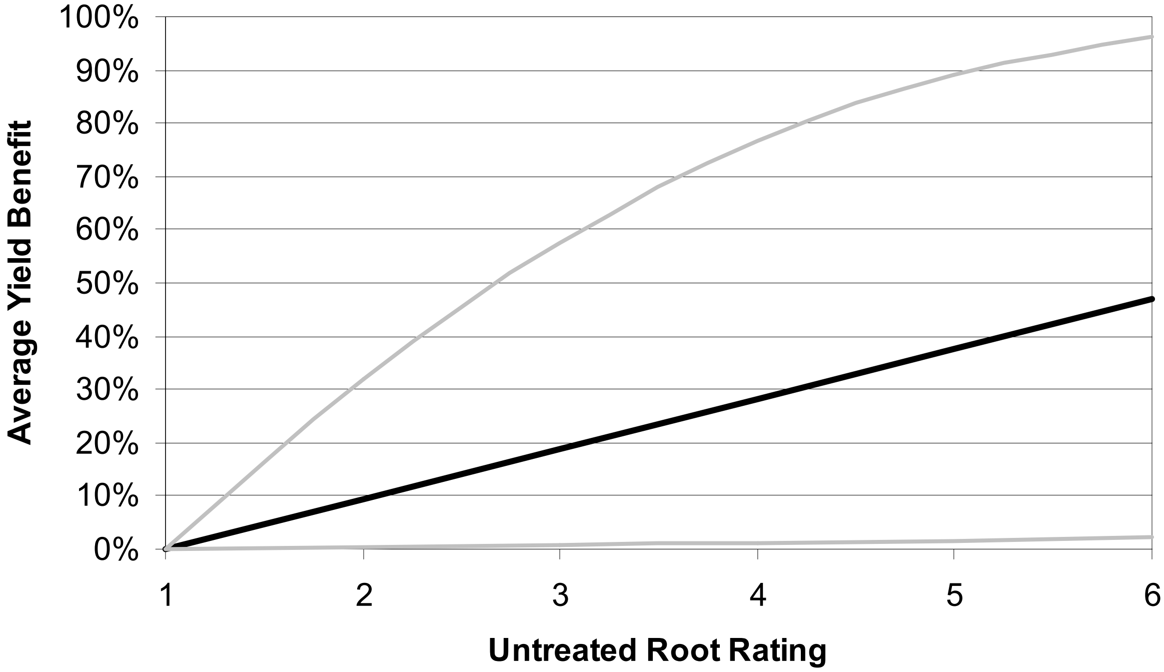

Figure 4. Average yield benefit for hybrids containing event MON 863 relative to no corn rootworm control (black) and the 95% confidence interval (gray).

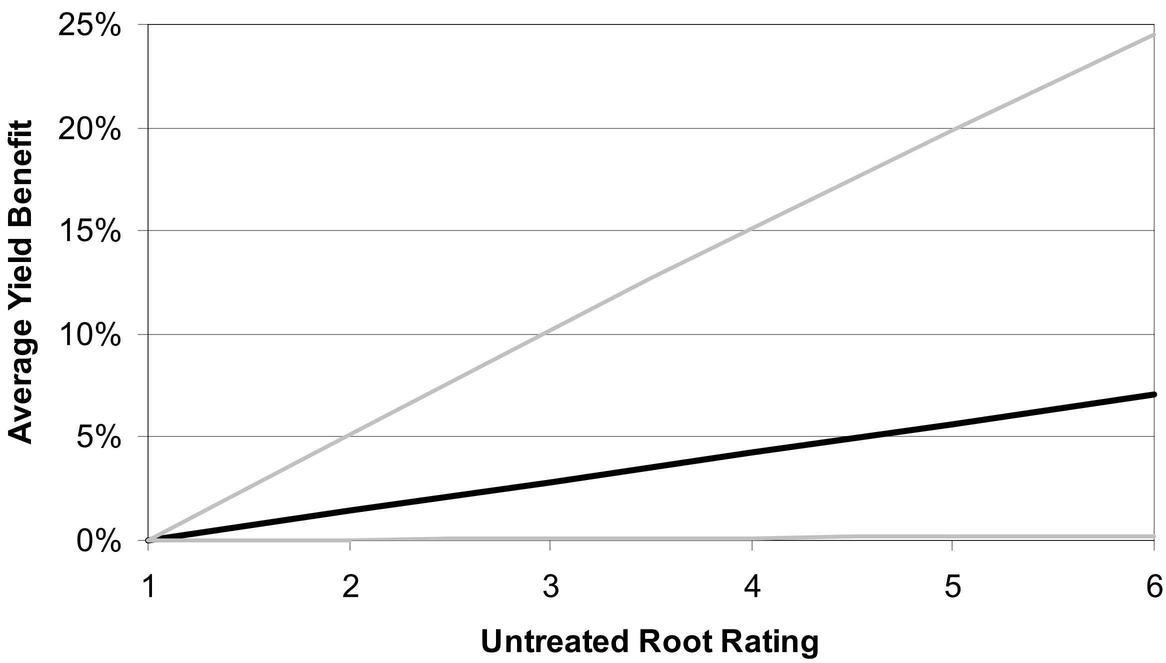

Figure 5. Average yield benefit for hybrids containing event MON 863 relative to control with a soil insecticide (black) and the 95% confidence interval (gray).