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Transgenic Rootworm Corn: Assessing Potential Agronomic, Economic, and Environmental Benefits

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Abstract

The potential benefits of transgenic rootworm corn (Cry3Bb1 protein) are expected to include: increased root protection; increased intangible benefits to farmers (safety of not being exposed to insecticides, ease of use and handling, time and labor savings, better pest control); increased economic benefits to farmers ($231 million from yield gains [$25-$75/acre relative to no insecticide control, $4-$12/acre relative to control with a soil insecticide] and $58 million in reduced insecticide risks and time savings); reduced incidence of corn stalk rot; and increased yield protection (9 to 28% relative to no insecticide use, 1.5 to 4.5% relative to control with a soil insecticide). If transgenic rootworm corn is planted on 10 million acres, the annual impact will be a reduction of 5,344,462 lb a.i. (75.2%) of insecticide use; increased resource conservation (3.07 to 5.23 million gal of diesel fuel equivalents conserved that would have been consumed in the manufacture and delivery of insecticides); increased water conservation (5,657,734 gal of water not used in insecticide application); conservation of aviation fuel (68,845 gal of aviation fuel not used); reduced farm waste (1,187,035 fewer insecticide containers used); increased planting efficiency; and improved safety to wildlife and other nontarget organisms.

Introduction

Corn (*Zea mays*) was planted on almost 80 million acres in the United States during 2002, and it accounts for more than 90% of the total value and production of U.S. feed grains (7). Corn is attacked by a variety of insect pests that can significantly reduce grain yield. Two of the most important pests in the Corn Belt are the western corn rootworm (*Diabrotica virgifera virgifera*) (Fig. 1), and the northern corn rootworm (*D. barberi*) (19). Additionally, the southern corn rootworm (*D. undecempunctata howardi*) and the Mexican corn rootworm (*D. virgifera zeae*) can be economically damaging in the Gulf Coast states and Texas, respectively (37). Corn rootworms cost farmers nearly $1 billion annually in crop losses and control costs (1). Current corn rootworm control strategies require the use of insecticides or rotation of corn with another crop. Both of these methods are used widely in the Corn Belt, but each has its limitations and has occasionally failed to prevent yield loss. Adult western corn rootworms have developed resistance to foliar-applied insecticides in some areas of the western Corn Belt (22). Likewise, in some areas of the Corn Belt, both the northern corn rootworm and western corn rootworm have adapted to crop rotation, which has long been considered an effective cultural control tactic. Eggs of the northern corn rootworm undergo extended diapause, i.e., they do not hatch the year after they are deposited, when the field is a crop other than corn; rather, they hatch two years later when corn has been planted in the field (5,18). The incidents of failure of crop rotation to control this insect have increased in recent years in Iowa (39). Western corn rootworm adults leave corn to lay eggs in soybean fields that may be planted to corn the following year (20). This problem has escalated the use of insecticides so that 33% and 39% of Illinois and Indiana farmers, respectively, apply insecticides to first-year corn fields for corn rootworm control (Wilson, Rice and Tollefson, *unpublished data*). Although management of corn rootworms will continue to include the use of insecticides and crop rotation, planting of transgenic (i.e., genetically engineered) corn that resists rootworm damage and protects grain yields will be an attractive alternative for many growers.

Fig. 1. Corn rootworm larva (Marlin E. Rice).

Monsanto Company has genetically modified the *cry3Bb1* gene derived from *Bacillus thuringiensis kumamotoensis* to express a Cry3Bb1 protein in corn (9). This Cry3Bb1 protein, a variant of the wild-type protein, is selectively toxic to some species of Coleoptera. The modified *cry3Bb1* gene is expressed in the MON 863 corn line and differs from the wild-type *cry3Bb1* gene by the addition of an alanine residue at position 2 of the protein and seven amino acid changes (12). The intended technical effect of the genetic modification is to protect corn roots from corn rootworm feeding. On February 25, 2003, the Environmental Protection Agency (EPA) approved transgenic MON 863 corn with the Cry3Bb1 protein for commercial use (10), and Monsanto will market the biotechnology as YieldGard Rootworm corn.

Gray (13) stated that “transgenic insecticidal cultivars offer great potential to serve as the most exciting and effective tool for corn rootworm control in the pest management arsenal.” In addition to insect control, the planting of transgenic rootworm corn is expected to generate numerous agronomic, environmental, and societal benefits. This article will discuss these expected benefits.

Potential Benefits of Transgenic Rootworm Corn

Increased root protection. Data from field studies indicate that transgenic rootworm corn will be as good as or better than soil insecticides in protecting corn roots from significant corn rootworm larval injury (38,40). YieldGard Rootworm and YieldGard Plus (a stacked hybrid with genes to control both European corn borer [*Ostrinia nubilalis*] and corn rootworms) were compared against the soil insecticide terbufos (Counter 20CR) and a nontransgenic hybrid with no insecticide (38). Products were evaluated for their consistency, which is the percentage of times a treatment limited feeding injury to 0.25 node or less (greater injury can result in economic yield losses). Both transgenic corn hybrids were 100% consistent in protecting roots from economic damage to roots, whereas the insecticide was only 63% consistent and the untreated nontransgenic offered no protection from insect damage (Fig. 2). Although transgenic rootworm corn does not offer total protection against larval feeding, university data suggest that the quantity of root injury is minor and should not translate into economic yield loss. An added benefit of transgenic rootworm corn is that root protection does not depend upon planting time, weather influences, calibration of application equipment, or soil conditions for optimum performance (24). However, the narrow spectrum of activity against corn rootworm larvae could also be a limitation when secondary pests (e.g., white grubs, wireworms, seedcorn maggots, grape colaspis) are present in economically damaging densities. In fields with secondary pest problems, corn producers may choose to protect the seed and seedling plants with seed-applied insecticides.

Fig. 2. Corn rootworm feeding injury to nontransgenic (near isogenic) corn (left) and YieldGard Rootworm corn (right) (Marlin E. Rice).

Yield protection and economic increases. Over typical ranges for corn rootworm populations, transgenic rootworm corn (genetic event MON 863) would provide a yield benefit of 9 to 28% relative to no insecticide use and a yield benefit of 1.5 to 4.5% relative to control with a soil insecticide (24). For a reasonable range of prices and yields, the predicted value of the yield benefit attributed to event MON 863 would be $25-$75/acre relative to no insecticide control and $4-$12/acre relative to control with a soil insecticide (24).

It is estimated that if transgenic rootworm corn had been planted in 2000 on 100% of U.S. corn acres treated with an insecticide (14.2 million acres) for corn rootworm control, at a cost that was equal to per-acre costs for corn rootworm insecticides, the total economic benefit would have been $460 million (3). Of this benefit, $231 million from yield gains would be gained by farmers, $58 million from reduced risks and time savings associated with reduced insecticide use would be realized by farmers, and $171 million would be realized by the technology developer and seed companies. The relative value of transgenic rootworm corn depends on the price of the transgenic seed, field performance, availability, and the price of close substitutes such as other corn rootworm-resistant varieties or insecticides (3). Although assumptions of higher prices and a more realistic estimate of adoption of transgenic rootworm corn (percentage of acres) would decrease the potential economic benefits, the benefits would still be substantial.

Intangible benefits for farmers. Farmers likely to adopt transgenic rootworm corn would recognize several intangible benefits that bring additional value to this new technology (3). Surveyed corn growers noted that advantages of a transgenic technology combined with an insecticide seed treatment (for minor seed-feeding or root-feeding pests) would include the safety of not handling an insecticide (30% of farmers), ease of use and handling (21%), all-in-one product insect control (21%), time and labor savings (14%), and better pest control (14%). The total value of these perceived benefits among likely adopters of the technology is $16.08/acre (Table 1) (3).

Table 1. Values placed on various characteristics by respondents likely to adopt transgenic rootworm corn relative to soil-applied insecticides (3).

Product Characteristic Value	**($/acre)**
Handling and labor time savings	1.94
Human safety	1.79
Environmental safety	1.46
Consistent control (reduced yield risk)	4.03
Equipment cost savings	1.57
Better standability (2 to 5% increase)	5.29
Total	16.08

Reduced insecticide use. Replacing insecticides with transgenic plants will reduce pesticide use against the target pest. Estimates of the U.S. corn acreage treated with insecticides for corn rootworms in 2000 range widely from 13,305,233 acres (6) to 14,196,990 acres (3) to 20 to 25 million acres (1). Using the conservative estimate of 13,305,233 insecticide-treated acres in 2000, if 10 million of these acres had been planted to transgenic rootworm corn, the result would have been a 75.2% reduction in insecticide use targeting corn rootworms. Calculating a number of assumptions (Appendix 1) based upon available data and a 10 million-acre replacement of insecticides with transgenic rootworm corn, the amount of insecticide (active ingredient) not placed into the environment can be reduced annually by 5,344,462 lb (or 534,446 lb for each 1 million acres).

Reductions in insecticide use as a result of planting transgenic corn hybrids to control insect pests have been documented. Corn farmers who planted transgenic *Bt* corn for control of European corn borer in five Midwestern states were asked whether insecticide use on their farms had decreased, increased, or stayed the same relative to insecticide use in the previous 5 years. Approximately half of the surveyed farmers had used an insecticide to manage European corn borer, and the percentage who decreased their insecticide use nearly doubled from 13.2% in 1996 to 26.0% in 1998 (32). Farmers who decreased insecticide use on their farms increased the percentage of transgenic corn acres they planted significantly from 19.7% in 1996 to 47.1% in 1998 (32). Transgenic *Bt* corn for control of European corn borer offers several advantages to the farmer, e.g., yield protection when the pest population is large, less insecticide in the environment, and less exposure of farm workers to insecticides (31). Similarly, a survey of 1,313 farmers from Illinois, Indiana, Iowa, Minnesota, and Nebraska predicted that the three primary benefits from transgenic rootworm corn would be less exposure of farmers to insecticides (69.9%), less insecticide used (68.5%), and better yields (53.2%) (Wilson, Rice, and Tollefson, *unpublished data*).

Reduced incidence of corn stalk rot. The stalk rot complex is the most serious, widespread disease problem in corn (26). Fields affected by stalk rot usually are damaged by more than one fungal species. *Gibberella*, *Fusarium*, and *Anthracnose* species are the most frequently reported stalk rot pathogens. Yield losses due to the stalk rot complex occur as a result of premature plant death and lodging. Stalk rot development is greatly affected by plant stress, and stalk rots often enter the plant through damaged roots (26). Transgenic corn that reduces the feeding of corn rootworm larvae on roots should significantly decrease the incidence of the stalk rot complex in corn.

Increased resource conservation. The manufacture of an insecticide requires an indirect energy input that is the sum of all energies in materials derived from the fuels in the manufacturing process (14). Modern pesticide manufacturing is an energy-intensive process that requires a complex series of chemical reactions that usually involve heating, stirring, distilling, filtering, and drying. Energy also is consumed in the processing and transporting of insecticides. All of these processes require direct energy inputs such as petroleum, gas, steam, or electricity.

Calculation of these energy inputs is a formidable task (14). Materials flow sheets and line diagrams for the production of many insecticides are, for the most part, confidential to manufacturers. When assessing the total energy input for a single pesticide application, a cumulative sum must be constructed that considers the indirect and direct energy inputs for the manufacture of the pesticide, the energy input for the formulation, packaging distribution and transport, and the direct energy used for application (14).

Approximately 2% of the energy used in agriculture is for pesticides, yet pesticides are the most energy-intensive agricultural input in energy sequestered per unit of material (15). For example, nitrogen fertilizers may require 50 to 70 GJ/t (gigajoules per metric ton) to produce, but the average amount of energy involved in pesticide production is approximately 260 GJ/t (15). Even though the energy use per area is small, any energy saved in the manufacturing and use of these pesticides can be very important.

Energy inputs are highly variable according to the hydrocarbon feedstocks used and the amount of heat and electricity used in the manufacturing process (33). Because pesticide information is proprietary, it is difficult to estimate energy uses exactly, except for those pesticides that are now off-patent (15).

The energy inputs for manufacturing, formulation, packaging, and transport of three types of insecticide formulations have been calculated as 311 MJ/kg for granules, and 257.3 MJ/kg for wettable powders and miscible oils (33). Other estimates for the total indirect and direct energy inputs average 214 MJ/kg active ingredient for 11 insecticides (14), 185 MJ/kg for five insecticides (11), or 315 MJ/kg for generic pesticides (23). For comparison, 1 gal of diesel fuel produces 146.3 MJ of energy (14). Most of these energy estimates are based on the production of chlorinated hydrocarbon, organophosphate, or carbamate insecticides, of which the latter two are still used for corn rootworm control. However, the trend is towards production of pesticides that are applied at a very low rate per unit area, although they are more energy intensive in manufacturing per unit (15).

Using data from several sources, I estimated the energy saved by replacing insecticides with transgenic corn rootworm technology on 10 million acres (an arbitrarily chosen value) (Appendix 2). The annual energy savings for the range (185 to 315 MJ/kg) of averaged energy requirements needed for insecticide manufacturing and transport are an estimated 3.07 to 5.23 million gal of diesel fuel equivalents.

Additionally, fuel and water are conserved by not applying liquid insecticides for corn rootworm control on 2,797,243 of the 10 million acres. I have estimated that 68,845 gal of aviation fuel would be saved and 5,657,734 gal of water would be conserved annually (Appendix 2).

Reduced farm waste. Corn rootworm insecticides are packaged in several types of containers. The most common packaging is a plastic sack containing 50 lb of granule insecticide. More recent innovations deliver granules in a self-contained system that prevents the on-farm user from contacting insecticide granules during planting; however, this type of container is not used for many products. Liquid formulations usually are packaged in 1- or 2.5-gal plastic jugs, occasionally in large bulk containers. I estimate that by not applying 5.34 million lb of insecticides, 1,187,035 fewer insecticide containers will be used (Appendix 1).

Increased farm worker safety. Nearly all corn rootworm insecticides (both granule and liquid formulations) are labeled as Restricted Use Pesticides by the EPA. These pesticides are products that, without additional regulatory restrictions, would have been found to cause unreasonable adverse effects on the environment, including injury to the applicator (8). Restricted Use Pesticides are moderately or highly hazardous to applicators by at least one mode of entry. Transgenic insect-control technologies pose no such safety risks to farmers (3). Use of transgenic rootworm corn would decrease exposure of farm workers to chemical insecticides. If transgenic rootworm corn were planted on 10 million acres, I estimate that farm workers would not be exposed to 5.344 million lb of insecticide per year (Appendix 1).

Increased labor efficiency. Savings in planting costs also may occur because the insecticide application equipment attached to the corn planter no longer will be necessary, although some farmers may choose to use insecticides and associated equipment on their refuge acres. If the insecticide application equipment is eliminated, larger seed boxes can be installed on the planter. The amortized purchase price of this equipment will mean a slight increase in per acre capital cost, but a larger hopper should cut seed refilling time in half, resulting in handling and labor time savings at a value of $1.94/acre (Table 1) (3). Planting time saved could be 5.32 h for each 1,000 acres of corn for equipment with no insecticide boxes. Also, there would be a reduction in aerial application, and 195 10-h work days of flying would be eliminated (Appendix 2).

Nontarget safety. Transgenic corn can conserve insect biodiversity in a corn field. The preimaginal development, survival, and field abundance of several species of beneficial predators (*Coleomegilla maculata*, *Orius insidiosus*, and *Chrysoperla carnea*) are unaffected by *Bt* corn expressing the Cry1Ab protein (29,30), which controls European corn borer larvae. Studies with transgenic *Bt* corn show that populations of the monarch butterfly (*Danaus plexippus*) are not acutely affected by the current corn biotechnology expressing the Cry1Ab protein and that the potential impact on the population of monarch butterflies is negligible (35,36). When larvae of *C. maculata* ingest Cry3Bb1-expressing corn pollen (event MON863), larval development, larval survivorship, and pupal weight were unaffected (21).

One group of beneficial organisms that will be exposed to Cry3Bb1 protein from transgenic rootworm corn is springtails (Collembola). These microscopic insects shred and humify organic matter and stimulate the growth of some beneficial soil fungi. Springtails can be abundant and surprisingly diverse in highly disturbed habitats such as agricultural fields. Because *Bt* toxins from transgenic plants can enter the soil ecosystem through the release of root exudates into the rhizosphere (4), springtails in the soil can be exposed to *Bt* toxins and their breakdown products over an extended period (17,34). A study in both irrigated and non-irrigated fields in Kansas revealed that corn roots expressing Cry3Bb1 protein did not significantly affect the numbers of springtails (Collembola) or three suborders of soil-inhabiting mites (Mesostigmata, Oribatei, or Prostigmata) (2).

These studies suggest that the current Cry proteins used in *Bt* corn pose no significant risk to populations of nontarget organisms. However, concerns have been raised that the benefits of transgenic corn are limited because the ecological effects on nontarget species are poorly documented and need additional study (27). Others (28) have countered that previous research may not necessarily predict all possible interactions, however, they acknowledged that if pest density is reduced -- whether by resistant plants, biological control agents, insecticides, cultural techniques, or any other methods -- there will be some impact on the biological community.

Insect resistance management. Insect resistance management is not necessarily a benefit of transgenic corn, but it is an issue that has influenced the use and performance of insecticides, and it will significantly influence the adoption and utilization of transgenic rootworm corn. The EPA will require an insect resistance management (IRM) plan of any transgenic corn developed commercially for control of insects. The IRM plan for corn rootworms requires a refuge of nontransgenic corn consisting of no less than 20% of a farmer's corn acreage with the same rotation history and planted within or adjacent to the transgenic rootworm corn (25). The refuge can be treated for corn rootworm larvae and/or other soil pests with soil-applied, seed-applied, or foliar-applied insecticides. This IRM strategy should extend the useful life of transgenic rootworm corn and help delay the development of insect resistance to the technology. In contrast, the EPA has not developed IRM strategies for any corn rootworm insecticide applied in the Corn Belt, although insecticides have been used for decades on millions of acres annually. There is no national pesticide policy that adequately protects against risks such as the development of insecticide resistance, which is a problem reaching crisis proportions with some crop pests (16). For example, western corn rootworms in some Nebraska counties are now 16.4 times more resistant to the insecticide methyl parathion because of excessive use over a wide area for control of adult beetles (22). Larvae in this same area also have increased levels of resistance to soil-applied insecticides. However, beyond the borders of Nebraska, aerial application of insecticides to prevent corn rootworm adults from laying eggs is not a common practice, and resistance to modern soil insecticides is not considered to be a problem. Soil insecticides applied in a narrow band in the region of the seed furrow or insecticides applied to the seed may provide a more durable resistance management tactic than aerial application, whereas an area-wide insecticide application for adult control is a classic situation for resistance development. Planting of transgenic corn for rootworm control over a wide area, without the inclusion of non-transgenic refuges, also would be a classic situation for resistance development and would greatly reduce the potential benefits of this biotechnology.

Conclusions

The corn rootworm species complex poses a serious and annual threat to the economic production of corn in the United States. Millions of pounds of insecticide are applied annually to control either the larval or adult stages of these pests, or corn fields are rotated with another crop to escape economic damage the next year. However, problems of incomplete crop protection with insecticides, the development of resistance to insecticides, and the biological adaptation of rootworms to crop rotation have diminished the effectiveness of these pest management tactics.

A review of the literature and interpretation of the available data suggest that there are potentially numerous environmental, societal, and economic benefits associated with including transgenic rootworm-control technology into a corn production system, compared with conventional, broad-spectrum corn rootworm insecticides. Specifically, these benefits would include increased crop protection, reduced use of insecticides, reduced incidence of stalk rot, increased yield protection, increased farm worker safety, increased energy and resource conservation, increased producer efficiency, increased economic return, and nontarget safety. Transgenic rootworm corn has the potential to transform integrated pest management efforts dramatically in the Corn Belt. However, this tool must be managed and used wisely according to the principles of integrated pest management and IRM if farmers except to sustain the benefits of the technology into the future.

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Appendix 1.

Assumptions used to estimate a reduction in insecticide and container use for management of corn rootworms annually.

Assumption 1. Acres treated with insecticide for corn rootworm control: 13,305,233 acres.

Assumption 2. Acres treated with granule and liquid insecticide formulations: Granule insecticides applied to 79.2% of treated acres (10,540,259 acres), liquid insecticides applied to 22.8% of treated acres (2,764,974 acres).

Assumption 3. Active ingredient per acre for corn rootworm control: 7,107,237 lb of insecticide (active ingredient), or 0.534 lb per treated acre.

Assumption 4. Acres planted to transgenic rootworm corn: 10,000,000 acres, resulting in a 75.2% reduction in insecticide-treated acres.

Assumption 5. Fewer insecticide applications: Farmers planting a transgenic corn rootworm hybrid make one fewer insecticide application per acre.

Assumption 6. Pounds of insecticide not applied for corn rootworm control: 5,344,462 lb of insecticide (active ingredient).

Assumption 7. Insecticide packaging: Granule soil insecticides are packaged in 50-lb sacks or 40-lb closed-system containers, and liquid insecticides are packaged in 1- or 2.5-gal containers, depending upon the product.

Assumption 8. Insecticide containers not used for corn rootworm control: 1,578,504 insecticide containers (1,385,658 granule containers, 192,846 liquid containers) used for insecticide delivery. Insecticide-treated acreage reduced by 75.2% results in 1,187,035 fewer insecticide containers.

Appendix 2.

Assumptions used to estimate farm worker safety and resource conservation by using transgenic rootworm corn annually.

Assumption 1. Increases farm worker safety: Use of transgenic rootworm corn on 10 million acres decreases farm worker exposure to 5,344,462 million lb of chemical insecticides.

Assumption 2. Reduces aerial insecticide application: Using a Thrush aircraft spraying 300 acres/h and operating at 100% efficiency, an acre of corn can be sprayed in 0.003 h. Adding machine labor, the time required to spray an acre of corn is 0.0033 h. 10,000,000 acres × 5.9% = 590,000 acres aerially treated; 0.0033 h per acre × 590,000 acres = 1,947 h; 1 work day = 10 h; 195 10-h work days of aerial application eliminated.

Assumption 3. Conserves aviation fuel: Using a Thrush aircraft operating at 100% efficiency and spraying 300 acres/h while consuming 35 gal of fuel per h. 590,000 acres/300 acres per h = 1,967 h; 1,967 h × 35 gal per h = 68,845 gal of aviation fuel saved.

Assumption 4. Conserves water: Liquid insecticides and gallons of water per acre applied with ground equipment:

Furadan 4F: 319,899 acres × 3 gal per acre = 959,697 gal water
Lorsban 4E: 362,858 acres × 5 gal per acre = 1,814,290 gal water
Regent 4SC: 1,386,452 acres × 1 gal per acre = 1,386,452 gal water
Regent 80WG: 105,765 acres × 3 gal per acre = 317,295 gal water

Insecticides aerially applied on 590,000 acres × 2 gal per acre = 1,180,000 gal water. Total water conserved from both aerial and ground application = 5,657,734 gal.

Assumption 5. Increases equipment efficiency: John Deere 16-row planter (30-inch row spacing) operating at 5 mph, plants 24.24 acres/h. 80,000 kernels per 50-lb bag = 268,800 kernels per 3-bu hopper/28,600 kernels per acre = 9.40 acres/hopper × 16 hoppers/planter = 150.38 acres planted for equipment with no insecticide boxes versus 75.19 acres planted with equipment with insecticide boxes.

Assumes time to place more seed in hoppers is offset by time that would have been required to fill up insecticide applicators and that cost of larger hopper is offset by cost of insecticide box. Time required to fill up is approximately the same but it is done half as often.

Assumption 6. Increases time savings: 1,000 acres of corn/150.38 acres planted for equipment with no insecticide boxes = 6.65 fill ups × 48 min/fill up = 5.32 h/1,000 acres; 1,000 acres of corn/75.19 acres planted with equipment with insecticide boxes = 13.30 fill ups × 48 min/fill up = 10.64 h/1,000 acres; time difference = 5.32 h of planting time saved/1000 acres of corn for equipment with no insecticide boxes.