POTENTIAL BENEFITS OF TRANSGENIC BT CORN FOR MANAGEMENT OF CORN ROOTWORMS

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Introduction

Corn, *Zea mays*, is widely produced in the United States and it accounts for more than 90% of the total value and production of U.S. feed grains (Economic Research Service 2002). Corn is attacked by a variety of insect pests that can significantly reduce grain yield. Two of the most important pests are the western corn rootworm, *Diabrotica virgifera virgifera*, and the northern corn rootworm, *Diabrotica barberi*. The Agricultural Research Service (2001a) estimates that corn rootworms cost farmers nearly $1 billion annually in crop losses and control costs. Current corn rootworm control strategies designed to prevent grain yield losses 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 derived from insect damage. The future of corn rootworm management may include planting of genetically- engineered corn that resists insect damage and protects grain yields. This article examines information on corn rootworms, current management strategies for their control, and the potential benefits of managing these pests with genetically-engineered corn.

Corn Rootworms

Species and general biology. The western corn rootworm and northern corn rootworm are two serious pests of continuous corn in the United States and Canada (Levine and Oloumi-Sadeghi 1991, Levine et al. 2002). Two additional corn rootworm species, the southern corn rootworm (twelvespotted cucumber beetle), *Diabrotica undecempunctata howardi*, and the Mexican corn rootworm, *Diabrotica virgifera zeae*, can be economically-damaging corn pests in the Gulf Coast states and Texas, respectively (Steffey et al. 1999).

In the Corn Belt, the northern and western corn rootworms have one generation per year. Eggs are laid in the soil during mid- to late summer and larvae typically hatch the following May and June. Adult beetles are present from late June until late September. The adults feed primarily on corn silks, pollen, and immature kernels. Western corn rootworms also feed on corn leaves and northern corn rootworms feed on the pollen of other plant species, including soybean.

Northern and western corn rootworm larvae can survive only on corn roots and a few species of grasses (Levine and Oloumi-Sadeghi 1991). Larvae feeding on corn roots can reduce the amount of nutrients and water that is taken up by the plant. Extensive injury reduces the ability of the roots to anchor plants and corn can "lodge" (i.e., fall over) in high winds and heavy rains, particularly when soils are saturated with moisture. Larval feeding also may facilitate infection of corn by root and stalk pathogens (Levine and Oloumi-Sadeghi 1991). All of these factors—root injury, lodging, and plant pathogens—can reduce grain yields.

Yield losses and economic impact. Yield losses due to corn rootworm larvae are variable and depend upon a number of criteria, including 1) insect population, 2) corn hybrid response to injury, 3) plant population, 4) planting date, 5) fertility levels, and 6) environmental conditions such as soil moisture, soil type, and wind. At the extreme, yield losses up to 85.8 bu/acre have been caused by corn rootworm larvae (Apple et al. 1977). A multiyear study (Apple et al. 1977) across several Corn Belt states compared two corn hybrids in carbofuran-treated and untreated plots. The study reported that corn rootworms reduced irrigated corn yields in Nebraska an average of 31.7 bu/acre during 1971–1974. Yield losses in Wisconsin during the same time period averaged 10.7 bu/acre. Early plantings in Missouri during 1971–1972 suffered 23.8 bu/acre loss, whereas data from a late season test in 1973 showed no crop loss. Ohio trials conducted in 1972 showed that corn rootworms were responsible for average grain yield losses of 9 bu/acre. In contrast, corn rootworm did not reduce corn yield in Minnesota experiments performed between 1971 and 1974.

A recent study suggests that farmers in east central Illinois should be concerned about western corn rootworm damage in first-year corn, although in that region a soil insecticide applied to first-year corn may not always protect sufficient yield to recover the cost of the treatment (Mitchell et al. 2002). In east central Illinois, the estimated average loss of 11.6%, returns the cost of a $12–$15 soil insecticide. However, as observed in the Apple et al. (1977) study, there is tremendous variability in corn rootworm damage, to the extent that the probability of grain yield loss accounting for less than $15/acre ranges between 32 and 45%, depending on assumed yield and corn price (Mitchell et al. 2002).

Changes in corn rootworm biology. There are two notable exceptions to the "typical" life cycle of corn rootworms. Northern corn rootworms exhibit extended diapause and western corn rootworm females lay eggs in alfalfa and soybean fields.

Extended diapause in northern corn rootworms occurs when eggs remain physiologically dormant and larvae hatch 2 to 3 years after eggs are laid in the soil (Steffey et al. 1999). This phenomenon has been documented in Iowa, Minnesota, Nebraska, and South Dakota. In 1964, most northern corn rootworm larvae hatched the following summer and only 0.3% of eggs in Minnesota remained dormant for more than 1 year (Chiang 1965). Nearly 2 decades later, 43.5% of northern corn rootworm larvae were hatching 2 years later (Krysan et al. 1984). The significance of extended diapause in corn rootworms is that it complicates management decisions for controlling this pest in first-year corn. Insecticides are not expected to be warranted for corn rootworms in rotated cornfields. When large northern corn rootworm populations infest unprotected, first-year corn, significant root injury is followed by lodging, pursuant harvesting complications, and grain yield losses. In Iowa, extended diapause has been confirmed in 57 counties. The largest concentration of damaged fields lies in the northwestern quarter of the state (Rice and Tollefson 1999). During the late 1990s, the problem spread into eastern Iowa (Jones and Cedar counties) and south central Iowa near the Missouri border.

Although extended diapause is widespread in four states, economic yield losses from northern corn rootworms remain inconsistent and difficult to predict. Between 1988 and 1993, data were collected from 59 first-year cornfields in northwestern Iowa that had experienced lodging from northern corn rootworm 2 years earlier (Tollefson and Rice 2001). Replicated, experimental plots, with and without an at-planting soil insecticide, were established in those fields and machine harvested.

After harvest, the incremental, economic benefit of using a soil insecticide was calculated using the market-year, average corn price ($2.00–$2.50 per bushel from 1988 to 1993) and an average soil insecticide cost of $12/acre. Yield increases that generated revenue in excess of soil insecticide costs were observed in only 20.3% of the fields. These data suggested that in fields where northern corn rootworm had caused lodging 2 years earlier, soil insecticide usage produced an economic return in one out of five fields (Tollefson and Rice 2001). Data from these large-scale, on-farm trials strongly suggested that a soil insecticide was not profitable in most first-year cornfields.

Corn insect management decisions are difficult to make because the effects of extended diapause cannot be predicted with a high degree of certainty. In the study fields in northwestern Iowa, adult northern corn rootworms were counted and a poor relationship was found between adult beetle counts one summer and corn root injury 2 years later (Tollefson and Rice 2001). In some fields, counts of three to four adult beetles per plant resulted in high root injury ratings 2 years later. In other fields, populations of 14 to 17 adults per plant did not translate into significant root injury 2 years later. This discrepancy between adult beetle counts and corn root injury 2 years later is probably a result of environmental extremes. Because nearly half of corn rootworm larvae hatch after eggs have been in the soil for 2 years, two consecutively cold winters could decrease egg survival, whereas two warmer than average winters could enhance egg survival. Even if the environment favored survival of eggs for 2 years, excessive soil moisture during hatching could drown significant numbers of larvae.

Extended diapause has also been discovered in eggs of the western corn rootworm but only at very low levels in Illinois (0.14%) and Ontario (0.21%) (Levine et al. 2002). There are no reports of crop damage from western corn rootworms exhibiting extended diapause.

Another change in corn rootworm biology is that, in recent years the western corn rootworm has begun to lay eggs in soybean and alfalfa, *Medicago sativa*, fields (Levine et al. 2002) even though the larvae cannot survive on roots of either crop. In 1987, western corn rootworm larvae caused severe injury to corn in east central Illinois that had been planted to soybean the previous year. Yield losses due to corn rootworm injury were "catastrophic (>50% of typical yields lost)" for many corn farmers (Levine et al. 2002). Since the late 1980s, western corn rootworm females laying eggs in soybean or alfalfa have been detected in Indiana, southern Michigan, western Ohio (Levine et al. 2002), and northeastern Iowa, where the ratio in first-year corn for western corn rootworms to northern corn rootworms was 9.3:1 (Rice 1999, Tollefson 1999).

Corn Rootworm Management—Current Strategies and Limitations

Corn rootworms in the Corn Belt are managed by three primary methods: crop rotation, soil-insecticide applications to control larvae, or insecticides applied to corn foliage to control adults.

Crop rotation. A common practice to control corn rootworms is crop rotation, for example, the planting of corn one year and a different crop, such as soybean, the next year. A corn–soybean rotation breaks the corn rootworm life cycle because, until a few years ago, eggs were not normally laid outside of cornfields and larvae cannot survive on soybean roots (Levine et al. 2002). As discussed above, the effectiveness of crop rotation in suppressing these pests has been diminished by 1) the behavioral change in western corn rootworms wherein the females now lay eggs in either soybean or alfalfa fields in the eastern Corn Belt, and 2) the extended diapause eggs of northern corn rootworms in the western Corn Belt (Levine et al. 2002, Tollefson and Rice 2001).

A corn–soybean–corn rotation is ineffective in breaking the life cycle of these 2 species in problem areas. Both species have, in a broad sense, developed resistance to the cultural tactic of crop rotation either by the delayed hatching of larvae (northerns) or the laying of eggs in soil outside of cornfields (westerns) but where corn will be planted the next year.

In areas where either species of corn rootworm has overcome the cultural control of crop rotation, farmers must chose from three options. The first option is to not use a soil insecticide on first-year corn, particularly if no information is available regarding insect population size or there has been no corn lodging problem. The second option is to use a soil insecticide in first-year corn. This option is recommended for control of northern corn rootworms only if extensive lodging occurred in the field 2 years earlier (Rice 1999b) or if western corn rootworm trap counts exceed 5 adults/trap/day in adjacent soybean one year earlier (Levine et al. 2002). The third option with northern corn rootworms and extended diapause is to rotate out of corn for 2 years. This biological solution will eliminate most northern corn rootworms from a field but it is, from an economic and agronomic perspective, the least desirable of the three options. Most farmers will not want to plant consecutive years of soybean in the same field because of concerns about soybean diseases.

Insecticides for corn rootworm larvae. Estimates of insecticide usage to control corn rootworms in the United States vary. Using 2000 Doane Research data, Alston et al. (2002) estimated that 14.2 million acres of corn received at least one insecticide application, at an average insecticide cost of $12.43/acre. The Agricultural Research Service (2001) estimated that 20 to 25 million acres is treated. Alston et al. (2002) estimated that, in continuous corn, 35.7% of acres received an insecticide for corn rootworms, whereas 10.2% of first-year corn acres had a rootworm insecticide. Most insecticides are applied at planting time as a granule formulation but, in recent years, chemical management options for corn rootworm larvae have broadened to include liquid formulations and seed treatments (Rice and Oleson 2001, Steffey 2001, Edwards et al. 2002, Wright 2002).

A common method of evaluating the performance of corn rootworm insecticides is to measure the level of root protection provided by the chemical. A typical approach is to measure the amount of root pruning caused by the larvae and assign a numerical rating to it on either a 1–6 or 1–3 scale. However, relating root ratings to insecticide performance can be a challenge. Accordingly, root protection is commonly measured by a standard called consistency (Rice and Oleson 1992). Consistency is expressed as a percentage of the time that insecticide-treated roots average a rating of 0.25 (1/4 root node eaten away) or less on the Iowa State node-injury scale (0–3) in the presence of a moderate-to-large population of corn rootworms. A high consistency number is indicative of good soil insecticide performance.

Over a number of Midwestern locations and years, no insecticide was 100% consistent in providing the protection necessary to prevent economic damage from corn rootworm larvae (Rice and Oleson 2001, Gray 2002). In Iowa, soil insecticide did not protect roots well during 2001. The best insecticide provided 59% consistency, whereas the worst provided by a granule insecticide was 27%. Interesting, the poorest performing insecticide was chlorpyrifos (Lorsban 15G), the most commonly used corn rootworm insecticide in the United States (Doane 2000).

In Iowa, the best consistency rating for a soil insecticide, averaged over a period of 4 years (1998–2001) was 82%. The failure of insecticides to sufficiently protect corn roots can be caused by a variety of reasons, including larger than average rootworm populations, soils that are too wet or dry, and later than normal planting dates (Rice and Oleson 2001, Gray 2002). Under such conditions, some products, notably the seed treatments, did not protect roots well from corn rootworm damage.

In recent years, the seed treatments tefluthrin (ProShield) and imidacloprid (Prescribe) have been marketed as corn rootworm control alternatives to soil-applied, granule insecticides. Iowa field tests indicated that those seed treatments did not consistently (16–27%) protect roots from corn rootworm injury, especially if the field had a moderate-to-large rootworm population (Rice and Oleson 2001). Gray (2001a) also noted the poor consistency of seed treatments and has stated that ProShield and Prescribe are not recommended for corn rootworm control by the University of Illinois.

Liquid insecticides also have been used against corn rootworm larvae. Their performance, like that of seed treatments, has not matched the higher level of consistency provided by the soil-applied granule insecticides. Gray (2002) stated that the performance of the liquids Regent 4SC (0% consistency) and Capture 2EC (5% consistency) was particularly troublesome at DeKalb, Illinois. Conditions at DeKalb were hot and dry throughout much of the summer. These findings suggest that, under adverse environmental conditions (very dry soil conditions) and large densities of corn rootworm larvae, growers may not be pleased with these two liquid products. In recent years, considerable interest has focused on the ease with which the new liquid products or seed treatments can be applied. However, consistency data collected to date suggest that performance of these new approaches has been lacking (Rice and Oleson 2001, Gray 2002).

Insecticides for corn rootworm adults. Except in Nebraska, application of insecticides through center-pivot irrigation systems (chemigation) or by aircraft for control of adult corn rootworms is uncommon. In Nebraska, adult corn rootworm control programs have been used to manage populations in continuous corn since the 1960s (Wright et al. 1999). The goal is to suppress adult populations and reduce egg-laying so that larval populations the following season will not cause economic loss. Adult control also may be used to prevent silk-clipping damage that may interfere with pollination, especially in seed production fields.

Management of corn rootworm adults requires more knowledge than management of corn rootworm larvae and it is more labor-intensive. An understanding of insect biology and factors that affect corn rootworm population dynamics and movement in corn is needed to effectively use an adult management strategy (Wright et al. 1999). First, fields must be scouted in late June through early July to identify when initial beetle emergence occurs, to identify which corn rootworm species are present, determine whether 10% of the females are gravid, and, ultimately, to determine when beetle populations reach an established economic threshold (Wright et al. 1999).

Management decisions may be complicated in cornfields that pollinate later than surrounding fields. Late-pollinating fields may act as a trap crop, attracting additional egg-laying females that increase the number of eggs laid and, ultimately, the number of corn rootworm adults, which makes successful management of corn rootworms using an adult-based strategy difficult (Wright et al. 1999). Additional factors, such as cool summer temperatures or frequent rains, may lengthen the period of adult emergence and reduce insecticide efficacy, complicating the timing of insecticide applications for adult control. Collectively, these observations mean that multiple insecticide applications may be needed to effectively manage the beetle population in a particular field (Wright et al. 1999). In Nebraska, repeated applications over a number of years have resulted in resistance and poor control of the insect to several popular insecticides (Agricultural Research Service 2001).

Area-wide management. A different corn rootworm control strategy is the federally sponsored government program known as area-wide management (Agricultural Research Service 2001a). Programs have been initiated in five geographic regions (eastern Illinois/western Indiana, Iowa, Kansas, South Dakota, and Texas) with the objectives of investigating alternative control tactics and implementing area-wide management of corn rootworms using semiochemical insecticide baits as a primary method of control.

The semiochemical bait is aerially applied and contains cucurbitacin (an extract from wild buffalo gourd root powder or watermelon juice) and insecticide (Agricultural Research Service 2001b). The cucurbitacins cause the beetles to feed almost exclusively on the sprayed droplets, thereby ingesting a lethal dose of insecticide. Two major advantages to the semiochemical bait are 1) the active insecticide ingredient is an ounce or less per acre, which is 95 to 98% less than in conventional sprays; and 2) the cucurbitacins are bitter so they do not appeal to other insects, making the application safe for bees and beneficial insects (Agricultural Research Service 2001b). The success of area-wide management, like the adult beetle spray programs in Nebraska, is inextricably linked to timely and accurate field scouting for adult beetles plus an understanding of the factors that affect corn rootworm population dynamics and movement in corn. These are obstacles that must be overcome if the area-wide management concept is to adopted outside of the current five experimental areas.

Farmer responses to insecticide use. Before the early 1990s, corn that was planted after soybeans seldom needed an insecticide to protect its roots from corn rootworm larval injury. By 2000, an average of 19.5% of farmers (n = 1,313) surveyed in five midwestern states were using an insecticide in first-year corn specifically for control of corn rootworms (Wilson et al. 2002, unpublished data). Responses were highly variable in the surveyed area but a higher percentage of first-year cornfields in Indiana (39.4%) and Illinois (33.1%) received an insecticide for corn rootworms than in Minnesota (3.4%), Iowa (8.5%), and Nebraska (12.9%).

The use of soil insecticides is a widely adopted practice by farmers and its use is increasing in first-year cornfields, but survey data suggests that Iowa corn producers prefer to avoid the use of insecticides. Lasley et al. (1989) surveyed 2,016 Iowa farmers regarding their perceptions of pesticide use to control crop pests. Seventy-eight percent of Iowa farmers agreed that modern farming relies too heavily upon insecticides and herbicides, 39% were very concerned about the aerial application of pesticides, and 33% were very concerned about the use of insecticides. Farmers were asked to judge nine potential health and safety hazards, including tractors, combines, balers, front-end loaders, grain dust, herbicides, air quality in confinement buildings, augers, and insecticides. The category of insecticides was ranked number one and given the highest rating, "very hazardous," by 77% of Iowa farmers over all other potential farm hazards (Lasley et al. 1989).

Insecticides and resistance. Chemical pesticides (herbicides, fungicides, and insecticides) have contributed significantly to farm productivity. Since World War II, average corn yields in the United States have more than tripled, partially because of chemical pesticide usage (General Accounting Office 2001). However, increased pesticide use has lead to several problems, including unintended effects on human health and offsite movement resulting in surface and groundwater contamination. Pesticides also can kill beneficial insects such as honey bees or natural enemies, such as lady beetles, that prey upon insect pest populations. Additionally, some pest insects have developed resistance to insecticides making them more difficult to kill and more costly to control (General Accounting Office 2001). A reduction in beneficial organisms and resistance of pests to insecticides can exacerbate a pest problem, making farmers more reliant on insecticides. This situation, known as the "pesticide treadmill," has lead the National Academy of Science to conclude that there was an urgent need for pest management alternatives that can complement and partially replace chemically based practices (General Accounting Office 2001).

Hybrid selection (traditional plant resistance). Currently, no commercial corn hybrid has a traditional source of resistance that is effective against corn rootworms. However, several hybrids may have traits that reduce damage from larval rootworm feeding. These characteristics include stalk strength, increased root mass size, or a capability to regenerate a root system after being damaged (Chiang 1973, Wright et al. 1999). All allow a plant to better tolerate rootworm feeding with a reduced likelihood of lodging (Wright et al. 1999). Of interest is the observation that root regrowth after larval injury may not be advantageous to yield (Gray and Steffey 1998). Working in Illinois with 12 popular corn hybrids over 4 years, they reported that root regrowth after larval injury typically had a positive effect on yield when soil moisture was inadequate; in contrast, root regrowth affected yield negatively when soil moisture was adequate.

Future of Current Management Strategies

The National Academy of Sciences reported that, without pesticides, the annual cost for food would increase by $225 per consumer (General Accounting Office 2001). However, pesticides are known or suspected to have unintended, adverse effects on the environment and human health, such as increased risks for cancer, neurological disorders, endocrine and immune system dysfunction; contaminated surface and ground water; and harm to wildlife and fish (General Accounting Office 2001).

In 1993, the Environmental Protection Agency Administrator and the Deputy Secretary of Agriculture, renewed the federal government's commitment to reduce pesticide use and associated risks (General Accounting Office 2001) by implementing integrated pest management (IPM) on 75% of total crop acreage by 2000. The U.S. Department of Agriculture estimated that IPM had been implemented on 76% of the corn acreage in 2000; however, the utilization of biologically based IPM practices ranged from less than 1% for disrupting pest mating to 18% for use of either biological pesticides on corn or planting crop varieties genetically modified to resist insects (General Accounting Office 2001). These low numbers suggest that IPM practices have been implemented in corn less than the overall adoption rate indicates (General Accounting Office 2001).

The U.S. Department of Agriculture has established a definition of IPM that is divided into four categories of practices: prevention, avoidance, monitoring, and suppression. The avoidance practice category includes planting crop varieties that are genetically modified to resist insects (General Accounting Office 2001). The General Accounting Office (2001) considers crop varieties that are genetically modified to resist crops, i.e., transgenic crops, as a biologically based IPM practice; 18% of corn acres in the United States were planted to these varieties in 2000 primarily for control of lepidopteran species such as European corn borer, *Ostrinia nubilalis*, and southwestern corn borer, *Diatrea grandiosella*.

IPM involves the use of pesticides in combination with a broad range of nonchemical pest management practices such as planting pest-resistant crops, protecting natural enemies of pests, implementing cultural practices that control pests, and careful monitoring of pest and beneficial organism populations (General Accounting Office 2001). The potential result of using IPM is a reduced reliance upon pesticides in agricultural and urban settings.

Transgenic Rootworm Corn

Monsanto Company has genetically engineered Cry3Bb1, a variant of the wild-type protein that is selectively toxic to some species of Coleoptera, to provide protection in corn against corn rootworms, *Diabrotica* species (Food and Drug Administration 2001). Monsanto Company used a modified *cry3Bb1* gene derived from *Bacillus thuringiensis kumamotoensis* (*B.t.k.*), to express a *B.t.k.* Cry3Bb1 protein in corn. The modified *cry3Bb1* gene expressed in the MON 863 corn line 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 (Food and Drug Administration 2001). The intended technical effect of the genetic modification is to protect corn plants from corn rootworm feeding on the roots. Gray (2001b) states 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."

Increased root protection. Early field data from several midwestern universities indicate that transgenic corn varieties will be as good as or better than soil insecticides in protecting corn roots from significant corn rootworm injury (Tollefson 1999, J. Oleson pers. commun.). Transgenic corn efficacious on rootworm does not offer total protection against feeding, but university data suggest that injury that does occur should not translate into economic yield loss.

Potential economic benefits. Relative to corn rootworm control with insecticides, Monsanto's YieldGard® Rootworm corn is expected to provide a yield gain of 0–7%, depending upon insect pressure. Its effectiveness does not depend upon timing, weather, calibration of application equipment or soil conditions (Mitchell 2002).

Alston et al. (2002) found that farmers likely to adopt transgenic rootworm corn recognize several intangible benefits that bring additional value to this new technology. Surveyed corn growers noted that advantages of a transgenic technology combined with a corn seed treatment (for minor seed-feeding or root-feeding pests) would include 1) the safety of not handling an insecticide (30% of farmers), and 2) 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 per acre (Table 1) (Alston et al. 2002).
The corn rootworm insecticides available to farmers are relatively safe, as determined by the Environmental Protection Agency, and when used according to product label directions. However, the transgenic insect-control technologies pose no safety risk to the farmer (Alston et al. 2002).

Alston et al. (2002) estimated that if YieldGard® rootworm corn had been planted in 2000 on 100% of U.S. corn acres treated with a pesticide (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. Of this benefit, $231 million from yield gains would be captured by farmers, $58 million would go to farmers in the form of reduced risks and time savings associated with reduced insecticide use, and $171 million to the technology developer and seed companies. The relative value of YieldGard® 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 (Alston et al. 2002). Different pricing assumptions and a more realistic adoption on the number of acres would decrease the potential benefits but they would still be substantial.

Reduced insecticide use. A likely outcome of replacing insecticide control with transgenic plants will be a reduction in pesticide usage against the target pest. Estimates of the U.S. corn acreage treated with insecticides in 2000 for corn rootworms ranges widely from 13,305,233 acres (Doane 2000) to 14,196,990 acres (Alston et al. 2002, Table 2) to 20–25 million acres (U.S. Department of Agriculture 2001a). Using the more conservative estimate of 13,305,233 insecticide-treated acres in 2000, 10 million acres planted to transgenic rootworm corn in the near future would result in a 75.2% reduction in insecticide use.

The use of transgenic corn hybrids to control insect pests does have a history of reducing insecticide usage. Corn farmers in five midwestern states that planted transgenic Bt corn for control of European corn borers 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 did not use insecticides to manage European corn borers, but of those that did, the percentage who decreased their insecticide use nearly doubled from 13.2% in 1996 to 26.0% in 1998 (Pilcher et al. 2002). 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 (Pilcher et al. 2002). Transgenic corn for control of European corn borer offers several advantages to the farmer, the most important being higher yields, less insecticide in the environment, and less exposure of farm workers to insecticides (Pilcher and Rice 1998). Similarly, a survey of 1,313 midwestern 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 et al. 2002, unpublished data).

Potential for reduced corn stalk rot. The stalk rot complex represents the most serious, widespread disease problem in corn (Munkvold and Hellmich 1999). Fields affected by stalk rot are usually damaged by more than one fungal species. Gibberella stalk rot, Fusarium stalk rot, and anthracnose stalk rot 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 roots (Munkvold and Hellmich 1999). Transgenic corn that reduces the feeding of corn rootworm larvae on roots should significantly decrease the incidence of the stalk rot complex in corn.

Yield benefits of transgenic rootworm corn. Mitchell (2002) calculated that, over typical ranges for corn rootworm populations, transgenic corn (genetic event MON 863) would provide a yield benefit of 9–28% relative to no insecticide use and a 1.5–4.5% yield benefit relative to control with a soil insecticide. For a reasonable range of prices and yields, Mitchell (2000) predicted that the value of event MON 863 yield benefit would be $25–$75/acre relative to no insecticide control and $4–$12/acre relative to control with a soil insecticide.

Increased resource conservation. Green (1987) stated that 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. 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. Energy consumed in getting an insecticide product to the farm can be estimated as the sum of direct and indirect energy inputs consumed in its manufacture, formulation, and distribution.

Calculation of these energy inputs is a formidable task (Green 1987). Materials flow sheets and line diagrams for the production of many insecticides are, for the most part, confidential to manufacturers. Green (1987) states that in 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.

Only 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 (Helsel 1992). For example, nitrogen fertilizers may require 50–70 gigajoules per metric ton (GJ/t) to produce, but the average amount of energy involved in pesticide production is approximately 260 GJ/t. Even though the energy use per area is small, any energy saved in the manufacturing and use of these pesticides can be very important.

Because pesticide information is proprietary, it is very difficult to estimate energy uses exactly except for those pesticides that are now off-patent (Helsel 1992). Pimentel (1992) calculates energy inputs as megajoules per kilogram (MJ/kg) for the production of several active ingredients, for example, methyl parathion (57.8 MJ/kg), carbofuran (452.5 MJ/kg), and carbaryl (152.5 MJ/kg).

Energy inputs are highly variable according to the hydrocarbon feedstocks used and the amount of heat and electricity used in the manufacturing process (Pimentel 1992). Additional energy inputs are required to formulate, package, and transport the insecticide to the farm for use (Pimentel 1992). Pimentel (1992) calculated the energy inputs for manufacturing, formulation, packaging, and transport of three types of insecticide formulations as 311 MJ/kg for granules, 257.3 MJ/kg for wettable powders, and 257.3 MJ/kg for miscible oils. For comparison, Green (1987) estimates one gigajoule of energy being equivalent to 8 gallons (U.S.) of diesel fuel; therefore, 1 gallon of diesel fuel produces 146.3 MJ of energy.

Using estimates from several sources, one can estimate the energy and manufacturing impacts of transgenic corn rootworm technology. Florida Cooperative Extension Service (2002) and Meir-Ploeger et al. (1996) estimate that between 238 MJ/kg active ingredient and 315 MJ/kg active ingredient, respectively, are consumed in the manufacture and delivery of pesticides. For these two estimates this translates into 3.95–5.23 million gallons of diesel fuel equivalents conserved that would have been consumed in the manufacture and delivery of insecticides.

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. A more recent innovative, the Lock-n-Load container, prevents the on-farm user from directly contacting insecticide granules during the planting operation. Liquid formulations are mostly packaged in 1- or 2.5-gallon plastic jugs although large bulk containers are occasionally used. It is estimated that by not applying 5.34 million lb of insecticides that 1,187,035 fewer insecticide containers will be used.

Increased farm worker safety. Use of transgenic rootworm corn can decrease farm worker exposure to chemical insecticides (Carpenter et al. 2002). Estimates are that farm workers would not be exposed to 5,340,000 lb of insecticide per year.

Producer efficiency. Savings in planting costs also may occur because the insecticide application equipment attached to the corn planter will no longer be necessary. With the insecticide application equipment 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 and thereby result in significant time savings (Alston et al. 2002).

Wildlife benefits/nontarget safety. Bt corn can enhance the biodiversity of cornfields because many beneficial insects fare better than when conventional cornfields are sprayed with insecticides. Moreover, field studies of biotechnology derived corn show that populations of beneficial insects are not adversely affected (Carpenter et al. 2002).

One group of beneficial organisms that may benefit from the planting of transgenic corn is springtails (Collembola). These insects range from 0.3 to 7.0 mm in length and are important and mostly beneficial members of the soil insect community. They shred and humify organic matter and stimulate the growth of some beneficial soil fungi. Springtails are abundant and surprisingly diverse even in such highly modified and disturbed habitats such as agricultural fields. However, the effects of these varieties on soil-inhabiting nontarget species such as springtails are unknown. Bt toxins from transgenic plants can enter the soil ecosystem in several ways, including incorporation of plant residues after the crop is harvested, and through release of root exudates into the rhizosphere (Angle 1994). Through these processes, organisms in the soil ecosystem can be exposed to Bt toxins and their breakdown products over an extended period (Jepson et al. 1994, Saxena et al. 1999). This potential for extended exposure to a variety of compounds may widen the range of affected species well beyond the highly specific host spectrum of Bt used as a microbial insecticide (Jepson et al. 1994). Therefore, any thorough evaluation of the effects of rootworm Bt corn should include assessing the impact on humus-forming arthropods such as springtails.

For surface-active species, Bitzer et al. (2002) found that the abundance of springtail species in either Illinois or Nebraska did not differ significantly between the Bt and non-Bt corn treatments. For soil-inhabiting species, only two species of springtails in Illinois differed in abundance in the Bt and non-Bt corn treatments, and in opposite ways. *Tullbergia simplex* was more abundant in non-Bt corn during 2000, whereas *Folsomides americanus* was more abundant in Bt corn during 2001.

Perceived limitations of transgenic rootworm corn. Any technology has its limitations, whether real or perceived, and these too must be considered by the potential adopters of transgenic rootworm corn. Alston et al. (2002) noted that the primary disadvantages of the biotech trait in corn combined with a seed treatment were that the technology might be too expensive (48%), lack of grain market acceptance (15%), and genetically modified organism (GMO) concerns (5%). Expense of the technology is a realistic concern but Monsanto's YieldGard® Rootworm corn is expected to be priced so that the seed premium is equal to the average cost of a corn rootworm insecticide treatment (Alston et al. 2002). If this is the case then the farmer should be indifferent toward the two methods on the basis of variable costs of control (Alston et al. 2002).

Conclusions

The corn rootworm species complex poses a serious threat to the economic production of corn in the United States. Millions of pounds of insecticide are annually applied to control either the larval or adult stages of these pests, or cornfields are rotated with another crop to escape damage the next year. However, the 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 suggests that, compared with conventional broad-spectrum corn rootworm insecticides, there are potentially numerous environmental, societal, and economic benefits associated with incorporating transgenic rootworm technology into a corn production system. Specifically, these benefits would include increased crop protection, reduced insecticide usage, reduced stalk rot, increased yield, increased farm worker safety, resource conservation, increased producer efficiency, increased economic return, and wildlife and nontarget safety. Transgenic rootworm corn has the potential to dramatically transform integrated pest management efforts in the Corn Belt; however, this tool must be managed and used wisely if farmers except to sustain the benefits of the technology into the future.

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Table 1. Values placed on various characteristics by respondents likely to adopt transgenic rootworm corn relative to soil-applied insecticides (Alston et al. 2002)

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 (2–5% increase)	5.29
Total	16.08

Table 2. Assumptions used to estimate a reduction in insecticide and container use for management of corn rootworms on a yearly basis

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

Assumption 2 – acres treated with granule and liquid insecticide formulations: granule insecticides applied to 94.1% of treated acres (12,515,574 acres) and liquid insecticides applied to 5.9% of treated acres (789,659 acres).

Assumption 3 – active ingredient per acre: 7,107,237 lb (3,233,807 kg) of insecticide (active ingredient), or 0.534 lb (0.242 kg) per treated acre, are applied for corn rootworm control.

Assumption 4 – acres planted to transgenic rootworm corn: transgenic rootworm corn is planted on 10,000,000 acres (4,046,860 hectares), 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: 5,340,000 lb of insecticide (active ingredient) not applied for corn rootworm control.

Assumption 7 – insecticide packaging: granule soil insecticides are packaged in 50-lb sacks or 40-lb Lock-n-Load containers, and liquid insecticides are packaged in 1 or 2.5 gallon containers, depending on product.

Assumption 8 – insecticide containers not used: 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% means 1,187,035 fewer insecticide containers.

Table 3. Assumptions used to estimate farm worker safety and resource conservation by using transgenic rootworm corn on a yearly basis

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Assumption 1 – increases farm worker safety: use of transgenic rootworm corn decreases farm worker exposure to 5.34 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 hour. Adding machine labor, the time required to spray an acre of corn is 0.0033 hour. 10,000,000 acres × 5.9 % = 590,000 acres; 0.0033 h acre^{-1} × 539,000 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 gallons of fuel per hour. 590,000 acres/300 acres h^{-1} = 1,967 h; 1,967 h × 35 gal h^{-1} = 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 acre^{-1} = 959,697 gal of water
Lorsban 4E: 362,858 acres × 5 gal acre^{-1} = 1,814,290 gal of water
Regent 4SC: 1,386,452 acres × 1 gal acre^{-1} = 1,386,452 gal of water
Regent 80WG: 105,765 acres × 3 gal acre^{-1} = 317,295 gal of water

Insecticides aerially applied on 590,000 acres × 2 gal acre^{-1} =1,180,000 gall of 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-in. operating at 5 mph plants 24.24 acres/h. 80,000 kernels/50-lb bag = 268,800 kernels/3-bu hopper/28,600 kernels planted/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 the same but it is done half as often.

Assumption 6 – increases time savings: 1,000 acres of corn/150.38 = 6.65 fill ups × 48 min/fill up = 5.32 h/1,000 acres; 1,000 acres of corn/75.19 = 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.