Prescriptive Use of Transgenic Hybrids for Corn Rootworms: An Ominous Cloud on the Horizon?

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The race continues to commercialize a transgenic insecticidal cultivar for the control of the corn rootworm complex, *Diabrotica* spp. There is no mystery about why the agribusiness sector is so keen in the development of this new and exciting approach to control corn rootworms. Metcalf (1986b) described rootworms as the billion-dollar complex based upon the costs associated with the purchase of soil insecticides and also due to crop losses caused by larvae and adults. On a national scale, farmers may eventually invest more than $400 million (annually) in transgenic technology fees (assumes a cost of $15 per acre) to prevent corn rootworm larval injury (Michael E. Gray [MEG] estimates). These resources would be invested to prevent an economic loss of $650 million (MEG estimates). Thus, the potential return on the investment for farmers nationally is estimated at roughly $250 million. These figures are based upon the continuing geographical expansion of the new western corn rootworm variant that does not restrict its oviposition to corn. The use of transgenic hybrids for corn rootworm control is expected to mirror or surpass that of soil insecticides, assuming the cost of a technology fee is comparable with that of a soil insecticide. So, a quick look at these numbers reveals the potential for a very large market for transgenic insecticidal cultivars for corn rootworms. The race is well underway, and currently, it remains unclear how close the contestants are to the finish line. Target dates of 2001 or 2002 have been suggested as realistic, at least for limited commercialization attempts.

Resistance Management Considerations for Transgenic Rootworm Hybrids

At the 1999 Crop Protection Technology Conference, I outlined many aspects of corn rootworm biology and ecology that should be considered in the development of resistance management plans for this important complex (Gray 1999). I suggest that the potential for resistance development by corn rootworms is much more acute than for European corn borer, *Ostrinia nubilalis* (Hübner). Reasons for this opinion include knowledge of dispersal characteristics of larvae (Suttle et al. 1967; Short and Luedtke 1970; Strnad et al. 1986; Strnad and Bergman 1987a,b; Gustin and Schumacher 1989; MacDonald and Ellis 1990; Strnad and Dunn 1990) and adults (Ruppel 1975, Witkowski et al. 1975, Coats et al. 1986, Grant and Seevers 1989, Youngman and Day 1993), narrow host range (Branson and Ortman 1967a–c; Branson and Ortman 1970; Branson 1971), injurious nature of two life stages within a single growing season, and a history of resistance development to several insecticides (Ball 1983, Metcalf 1986a, Gray and Luckmann 1994, Meinke et al. 1998). Development of sound resistance management strategies for the deployment of transgenic corn rootworm cultivars is essential to prolong the usefulness of this technology. Even with these strategies in place, in my opinion, resistance will develop eventually. Are there resistance management ideas worthy of consideration for corn rootworms that differ from the approaches currently recommended for European corn borer? I propose that the answer to this question is "yes."

Transgenic Insecticidal Cultivars: Examples of Pest Management Tools?

If a producer elects to purchase a *Bacillus thuringiensis* (Bt) hybrid for European corn borer control, is this an example of a sound pest management approach? Some would argue that it is because the use of a Bt hybrid is nothing more than using host plant resistance to prevent economic loss. After all, host plant resistance is the "cornerstone" of many well-designed IPM programs. Others contend that the purchase of Bt seed for European corn borer control is no better than using a broadcast application of an insecticide with no scouting input or knowledge of spring densities of this pest. The truth lies somewhere in between these viewpoints. It is true that the purchase of transgenic seed to control European corn borer occurs most often in the fall or early winter preceding the upcoming growing season. Entomologists have never had much success in predicting subsequent infestations of European corn borer even when equipped with knowledge of fall densities of this pest. Instead, they often speak in general terms concerning the likelihood of an infestation (Briggs and Guse 1986). For example, based on historical records, producers in northwestern counties of Illinois are more likely to have economic infestations of European corn borer than are farmers south of Interstate 70. But, it is a stretch to say that producers equipped with this knowledge are making informed pest management decisions when they decide to invest in the Bt technology for European corn borer control. Unfortunately, scouting fields and using economic thresholds does not work when it comes to making decisions about the use of a Bt hybrid for European corn borer control. In the real world, after they have reviewed their bottom lines for the season, farmers will continue to make educated guesses about the best seed choices for the upcoming growing season, Bt or non-Bt, being just one aspect of the seed selection process. One thing is for sure, most producers are not asking themselves the philosophical question: "Does the use of a Bt hybrid fall within the framework of an IPM program?" Although issues such as the development of resistance remain a concern of producers (Pilcher and Rice 1998), profitability drives crop production and protection decisions. As mentioned, scouting and the use of economic thresholds do not work well in deciding whether to purchase a Bt hybrid for European corn borer control. However, this is *not* true for corn rootworms, and future management decisions that hinge upon whether to use a transgenic insecticidal cultivar for this pest complex may indeed rely upon the fundamental components of IPM, scouting, and economic thresholds.

Frequency of Corn Rootworm Infestations within Farmers' Fields

How frequently do farmers face economic infestations of corn rootworm larvae within their fields? Bigger and Petty (1965) conducted surveys (1954–1963) of 452 producers' fields (untreated strips) in Illinois and found that 28% (range for the 10 years, 12–43%) of the fields were infested with northern corn rootworm. The average percentage of plants infested was 18% (range for the 10 years, 11–27%). These figures are good estimates of the percentage of fields infested only with northern corn rootworm. Western corn rootworm was detected for the first time in Illinois during 1964. Research conducted in Iowa led Turpin et al. (1972) to predict that 36% of continuous (nonrotated) cornfields in Iowa exceeded the economic injury index of 2.5 (Hills and Peters 1971). They offered the following admonition concerning soil insecticide use and corn rootworm injury: "Iowa in 1969 had 10 million corn acres, of which ½ (5 million acres) followed a corn crop in 1968. Farmers used insecticides on 72% of the corn-following-corn acres in 1969. Since the prediction equation showed a need for insecticides on 36% of the corn-following-corn acres, the other 36%, or 1.8 million acres, of Iowa corn ground was treated needlessly for rootworm control." Research conducted (1972–1974) in the eastern Corn Belt by Turpin and Thieme (1978) revealed that corn rootworm larvae occurred in 34% of 234 Indiana cornfields. Average root ratings in producers' control strips (no soil insecticide used) exceeded a root rating of 2.5 (Hills and Peters 1971) in only 3.4% of the fields. By conducting a series of on-farm experiments in Illinois during 1990 and 1991, Gray et al. (1993) determined that 26 of 58 producers' fields (45%) had root injury at or above an average root rating of 3.0, the so-called economic injury index. In the Illinois study, only 7 of 58 producers' fields (12%) had root injury equal to an average root rating of ≥4.0 in untreated areas of their fields. Root ratings of ≥4.0 typically predispose a plant to lodging and subsequent yield loss. These data confirm that Illinois' producers use soil insecticides on more continuous corn acres than necessary for corn rootworm control. Yet in the early 1990s, a large percentage of continuous corn acres in Illinois (2.5 million acres, 88% of continuous corn in Illinois) was being treated with soil insecticides each spring (Pike and Gray 1992).

Results from more recent studies conducted in eastern states also suggest that many cornfields do not support economic infestations of corn rootworm larvae. Davis and Coleman (1997) found that only 30 and 50% of New York cornfields exceeded a gain threshold of 6.4 bu/acre in 1993 and 1994, respectively, at a soil insecticide cost of $16/acre and grain valued at $2.50/bu. Kuhar et al. (1997) conducted field investigations (1993 and 1994) in 32 continuous cornfields in Virginia. They determined that only 28% of the fields had root injury that exceeded a rating of 3.5 in control strips (no soil insecticide used); only 19% of the cornfields had economic losses due to rootworm injury. They concluded that much of the soil insecticide used is unnecessary on the continuous corn acres within Virginia.

I propose that the take-home message of these papers is the following: Research to date indicates very clearly that the investment in a transgenic insecticidal cultivar for corn rootworm control will not pay dividends on all planted corn acres. Economic infestations of corn rootworm larvae do not occur in most cornfields. This knowledge supports the use of established scouting techniques for adult corn rootworms in late summer and the use of transgenic hybrids for corn rootworms the subsequent spring in only those fields that exceeded economic thresholds.

Predicting Economic Infestations of Corn Rootworms: A Precise Science?

Adult corn rootworm management programs have been recommended and practiced in many states for more than 2 decades. The use of broadcast insecticide applications to suppress oviposition by corn rootworm females is much more common in the western Corn Belt, especially in Nebraska. Although adult control programs are not as common in the eastern Corn Belt, Gray and Steffey (1999) offered the following recommendation regarding this rootworm management approach: "Another alternative is controlling rootworm adults in corn to prevent them from laying eggs. If the number of beetles reaches or exceeds 0.75 per plant, apply an insecticide when 10 percent of the females are gravid (with eggs). Continue to monitor fields weekly after treatment for rootworm beetles. A second application of an insecticide may be necessary if the number of beetles reaches or exceeds 0.5 per plant . . . Scout for rootworm beetles from mid-July through early September 1999 to determine the potential for rootworm larval damage in 2000."

Economic thresholds used for beetle management programs should reflect whether a field has just been rotated recently or has been devoted to corn production for many years. Godfrey and Turpin (1983) determined that first-year cornfields (rotated cornfields) had greater percentages of female western corn rootworm adults with greater ovarian development than adults found in continuous cornfields after July 30. They suggested that economic thresholds for adults in first-year cornfields should be 50% less than thresholds used in continuous cornfields. Weiss and Mayo (1985) recommended that beetle counts should be adjusted according to the plant population within a field. By doing so, they concluded that more accurate estimates of adult densities and, more importantly, potential oviposition could be made. Naranjo and Sawyer (1989) discovered that the oviposition per female was not as great in earlier-planted and earlier-flowering fields and suggested that thresholds should be adjusted upward for early-planted fields compared with late-planted fields. Riedell et al. (1992) indicated that irrigation reduced losses caused by corn rootworm larvae when plants were exposed to hot and dry weather. Maize grown under irrigated conditions suffered less yield loss under equal levels of rootworm larval injury compared with dryland maize. They suggested that economic injury levels and thresholds should be adjusted accordingly for irrigated production systems. This review of the literature suggests clearly that entomologists have considerable knowledge about how economic thresholds for corn rootworms should be adjusted according to a variety of crop-production parameters.

For decades, entomologists at land-grant institutions have recommended that producers scout their fields for corn rootworm adults so that decisions can be made to suppress oviposition or, in some instances, to make more responsible choices regarding the use of a soil insecticide the following spring. In deciding whether to use a soil insecticide, Gray and Steffey (1999) recommended the following thresholds: "Alternate corn with another crop when possible, particularly in fields where rootworm beetles averaged 0.75 or more per plant, or if the soil insecticide did not adequately protect the roots in 1998. If you intend to grow corn after corn and if rootworm beetles averaged 0.75 or more per plant in corn after corn or 0.5 per plant in first-year corn last summer, apply a rootworm soil insecticide at planting time."

Among entomologists, some disagreement remains regarding the reliability of these recommendations to identify accurately those fields that do not require an application of a soil insecticide at planting. Stamm et al. (1985) evaluated the utility of an adult threshold for western corn rootworm in making larval control recommendations to Nebraska producers. In all, 74 fields were used during their 3-year experiment. Cornfields with beetle densities of less than one beetle per plant each week throughout August were considered unlikely candidates for economic larval injury the following year and soil insecticides were not recommended. If adult densities exceeded one beetle per plant in August, farmers were advised to use a soil insecticide at planting the following spring. Stamm et al. (1985) reported that this pest management approach was reliable >80% of the time. If the economic threshold was reduced to 0.75 beetle per plant, the predictive reliability increased to 90%. A root-injury index of 2.75 (Hills and Peters 1971) was considered as the economic injury index for this research endeavor. During this study, the percentage of fields treated with soil insecticides declined from 90 to 28%, suggesting that scouting for adult corn rootworms and using an economic threshold can be a viable pest management approach for corn rootworms.

Is scouting and the use of thresholds really that simple for corn rootworms? The answer is "no." The findings of Foster et al. (1986) are in direct contrast to those reported by Stamm et al. (1985). Densities of adult corn rootworms were determined in each of 3 years (1979–1981) in 31, 43, and 44 Iowa cornfields, respectively. These researchers found that adult economic thresholds failed to accurately predict economic larval damage in >50% of the fields. At the conclusion of their research, they offered the following controversial statement "The optimal strategy for managing corn rootworms in Iowa in our study was not to sample for adults and always to treat corn following corn with a soil insecticide at planting time." They maintained that the current sampling procedures and adult thresholds were not useful in deciding when no insecticide treatments were needed.

So, can economic infestations of corn rootworm larvae be predicted accurately? Are sampling and the use of economic thresholds for corn rootworms an art or a science? Honestly, it depends on the research that you cite. However, what are the consequences of repeatedly erring on the side of treating for corn rootworms when economic infestations do not exist? And, as mentioned previously, in most cornfields, larval densities are below the economic injury level.

Corn Rootworms and Insecticide Resistance: Here We Go Again

Adult corn rootworm management practices have been recommended by consultants in Nebraska for decades and have been subscribed to by many producers as an alternative to soil insecticides. Unfortunately, the broadcast adulticides were usually the sole management tactic used by many farmers. Meinke et al. (1998) confirmed that western corn rootworm has developed resistance to methyl parathion (16.4-fold) and carbaryl (9.4-fold) in areas of Nebraska where applications of these products have been common for years. The F1 generation also displayed resistance characteristics, confirming the heritability of this trait. Excessive use of broadcast chlorinated hydrocarbon insecticides (aldrin, heptachlor) for corn rootworm control from the late 1940s through the early 1960s resulted in the development of resistance (Ball and Weekman 1963). The resistant western corn rootworm strain spread rapidly, and by 1980, corn production across much of the Corn Belt was affected (Metcalf 1986a). Because of the failure of crop rotation as a viable corn rootworm management approach in an increasing area of the eastern Corn Belt, the spread of an organophosphate-resistant strain of western corn rootworm would pose a significant corn production challenge to producers. Corn rootworms have shown repeatedly that they are superbly capable of adapting to a variety of insecticides and even to a cultural practice. Any notion that they will not develop resistance to transgenic insecticidal cultivars at some point is foolhardy.

Prescriptive Use of Transgenic Insecticidal Cultivars for Corn Rootworms

Unlike the use of transgenic insecticidal cultivars for European corn borer management, the use of transgenic hybrids for corn rootworms could work in concert with existing scouting programs and established economic thresholds. By monitoring their fields for corn rootworm adults in late summer, farmers could base their decision to use transgenic rootworm hybrids the following spring upon scouting input and knowledge of thresholds. Crop consultants and other professionals in the agribusiness sector could take a very active role in this decision-making process.

Should the use of a transgenic insecticidal cultivar for corn rootworms be legally tied to documentation that indicates that the field in question has been scouted and an economic threshold for corn rootworm adults has been exceeded? Recall that nearly half of the continuous cornfields do not have economic infestations of corn rootworm larvae. Thus, if transgenic cultivars were planted on only half of these fields, in effect, we have created a large refuge across the landscape. Arguably, this refuge would reduce the selection pressure for resistance development. If prescriptive use of transgenic hybrids for corn rootworm control is mandated, should the same argument be made for soil insecticides?

To date, the planting-time use of soil insecticides (banded applications) has not resulted in the development of resistance. Nor is resistance to these products anticipated. Why? In a 3-year study, Gray et al. (1992) reported that greater western corn rootworm emergence occurred in insecticide-treated (carbofuran, chlorpyrifos, and terbufos) areas compared with control plots (no soil insecticide used) in some years. Although soil insecticides usually offer adequate root protection, they are not population-management tools; that is, they do not suppress densities of corn rootworms across the agricultural landscape. Despite this feature that may be perceived as a disadvantage, banded applications of soil insecticides have played the role of a resistance-management tool very well for decades. Because not all corn rootworm larvae are exposed to soil insecticides, in-field refuges have been created unwittingly by farmers each spring. Unlike soil insecticides, transgenic insecticidal cultivars probably will be powerful population-suppression tools, placing enormous selection pressure on the corn rootworm population. Important differences exist between soil insecticides and transgenic hybrids, from a resistance-management perspective, and on this basis, a prescriptive approach for transgenic cultivars seems more justified for transgenic cultivars. To be consistent with this line of reasoning, an argument for the prescriptive use of broadcast adulticides for corn rootworm control also can be made.

If we accept that the genes used within a transgenic cultivar for corn rootworms are a natural resource (belonging to no one) and, therefore, should be preserved, a philosophical debate ensues. Synthetic insecticides that are used to control insects are, by definition, synthesized, and although their loss due to resistance development by an insect population is regrettable, it pales in comparison to the loss of a natural resource squandered through misuse within a pest management program. From my vantage point, the stakes are greater when it comes to preserving the long-term integrity of transgenic cultivars for corn rootworm control compared with insecticides. If this argument is accepted, a prescriptive approach for the use of transgenic cultivars for corn rootworm control is worthy of broad consideration by the scientific and regulatory community.

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