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Environmental Opportunities and Challenges of Genetically-Engineered Crops

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Agricultural production of food, feed and fiber cause significant changes to the environment. Tillage, crop monocultures, fertilizer and pesticide use may adversely affect soil quality, water quality and biodiversity on and off farms. An ongoing challenge for agriculture is the need for sustainable systems while maximizing production. Environmentally sound and sustainable agricultural management practices available to producers include soil conservation, crop rotation, and integrated pest and resistance management.

Genetically-engineered (GE) crops were commercially available starting in 1995 in the United States. Because GE crops in the United States are planted on a large percentage of acres in production agriculture, any impacts on the environment could have a large cumulative effect. In 2009 the percent of acreage planted to GE crop cultivars was 85% for corn, 88% for cotton, and 91% for soybeans, and GE cultivars also represented a high proportion of canola and sugar beet acres (National Research Council, 2010). This amounts to more than 150 million acres, or about half of all land where crops are grown (National Research Council, 2010). Evaluating the relationship between GE crops and agricultural sustainability requires a baseline or reference point for comparison. Here we focus on what GE crops in the United States have replaced—non-GE corn, cotton and soybeans grown conventionally—as a reference for understanding the contribution of GE crops towards sustainable agriculture. Currently other alternative production practices like organic farming for corn, soy and cotton are rare.

Opportunities for Environmental Sustainability in Agriculture

Current GE crops are used to help farmers manage weeds and pests. The most commonly used GE crops have been engineered for two main traits: herbicide resistance (HR) and insect resistance (IR). HR cultivars allow farmers to use a specific herbicide to control weeds without harming crops. Currently most of the HR crops planted are resistant to glyphosate. IR cultivars currently available in the market are engineered to produce toxin(s) from a ubiquitous soil bacterium, *Bacillus thuringiensis* (Bt). Bt proteins in IR crops kill specific insect pests when they eat the plant. Some GE crops incorporate both HR and IR traits.

HR and IR crops have changed what herbicides and insecticides are used as well as the quantities applied. Not surprisingly, since the introduction of GE varieties of corn, cotton and soybeans resistant to glyphosate, the amount of glyphosate used has increased substantially while the quantity of other herbicides used has decreased. However, because glyphosate is applied at higher rate than other herbicides and sometimes applied more than once per season, the total quantity of active ingredients for all herbicides applied has increased in soybeans and cotton but has decreased in corn. The quantity of insecticides used on corn and cotton has decreased as more acres have been planted with IR cultivars, although not all decreases in insecticide use are attributable to the use of IR crops (National Research Council, 2010).

Relative to the herbicides it has replaced, glyphosate presents fewer adverse effects on the environment. Glyphosate binds tightly to soil, lowering the potential for movement off-site and into water. It persists a relatively short period of time, on the order of a few months, so that accumulation over seasons is unlikely. It has low toxicity compared to its alternatives although some formulations of glyphosate can be toxic to amphibians and aquatic organisms (National Research Council, 2010).

The use of HR soybeans and cotton is complementary with soil conservation tillage practices of not tilling fields (no-till) and leaving a high percentage of crop residue on the soil surface rather than plowing it into the soil (National Research Council, 2010). These soil conservation practices increase soil quality and soil retention on farm fields and also reduce the movement of soil sediment, nutrients and chemicals off-site and into surface water. Thus, conservation tillage will improve soil quality over time compared to fields under aggressive tillage practices. Given the environmental characteristics of glyphosate and the increased adoption of soil conservation practices accompanying the adoption of HR crops, one would predict improvements in surface water quality in areas of high GE crop adoption. However, data and analyses to track the actual impacts of the widespread adoption of GE crops on water quality are not available with our current investment in water quality monitoring. Therefore, we are missing key information for assessing the impact of GE crops on sustainability.

The effect of current GE crops on biodiversity, and in particular, on species like beneficial insect predators, pollinators, and parasitoids—organisms such as wasps and flies that develop on a single insect host—has been the subject of considerable discussion and research. Although IR crops typically target specific insect pests, other species, especially close relatives, could be affected by the Bt toxin if they eat the plant, the pollen, or the decaying IR crop residue. Predators and parasitoids could also suffer when feeding on prey negatively affected by the Bt toxins. In field experiments, the net effects of IR crops on other insect species depend on the extent of insecticide use reduction. When IR crops completely replace insecticide treatments, higher numbers of predators occur in fields where IR crops are used in place of conventional insecticides. When IR crops replace conventional crops not treated with insecticides, slightly fewer predators occur in IR cotton and no detectable differences are found in IR corn (Wolfenbarger et al., 2008). Extrapolation of these results to all cotton grown in the United States is difficult because most cotton is sprayed with insecticides and total replacement of insecticides by IR cotton has generally not occurred. On the other hand, IR corn would be expected to have a neutral effect on beneficial predators and parasitoids because field corn is treated with little or no foliar insecticides in most corn production areas (National Research Council, 2010).

Biological control, or the use of predators and parasitoids to control insect pest populations, is a key component of integrated insect pest management. No general pattern of how IR crops affect biological control has yet emerged from field studies conducted so far; in some cases, biological control has been enhanced, and in others, control is equivalent or reduced. With respect to pollinators, honey-bee adults and larvae were not harmed by Bt pollen or Bt proteins in IR crops, but too few pollinators have been studied to fully evaluate the impacts of IR crops on pollinators as a whole.

Effects on the abundance of arthropods, such as insects and spiders, in HR crop fields depend on whether weeds are controlled more or less effectively than in crops grown conventionally. When HR technology provides better weed control, arthropods richness tends to diminish, and the reverse is true when conventional weed control is superior. However, weed management is not the largest influence on the abundance of beneficial organisms, as three to more than a tenfold difference occurred in abundance among different crops and within a given production season, compared with a twofold difference associated with weed management (National Research Council, 2010).

Soil organisms decompose plant residue, cycle nutrients and improve soil structure. Soil organisms tend to have greater abundance or biomass in no tillage crop production systems than in conventional tillage systems because soil is disturbed less. While glyphosate can alter the microbial composition of the soil surrounding plant roots, the impacts of such changes cannot be interpreted from the scientific studies conducted thus far. Studies of the interaction of tillage and glyphosate use in HR crops have suggested transient benign effects of glyphosate and neutral, or in one case favorable, effects of conservation tillage on the soil microorganism communities. Most assessments of effects of Bt proteins from IR crops on soil microorganisms and other organisms also found that these proteins do not substantially alter populations and measured functions (National Research Council, 2010).

Deployment of IR crops can have desirable or less desirable regional effects on insect pest population dynamics. Evidence indicates that high adoption rates of IR corn and IR cotton can decrease populations of some target insect pests at a regional level, suggesting that the effect of IR crops on pests can extend outside the field where the crop is planted (Carrière, Crowder, and Tabashnik, 2010). Such regional changes could lower insecticide use in fields of non-IR crops. On the other hand, lower use of insecticides in IR cotton has sometimes increased outbreaks of insect pests affected by insecticides but immune to the Bt toxin(s). Furthermore, control of certain insect pests by corn producing the Bt toxin Cry1Ab may have conferred a competitive advantage to the western corn earworm (*Striacosta albicosta*), a pest that is not affected by this Bt toxin (Dorhout and Rice 2010). Such competitive advantage may explain the recent spread of the western corn earworm to the east of the U.S. Corn Belt, where it has caused significant damage to corn and triggered insecticide applications.

Challenges for Sustainability

A single insect pest or weed may produce several millions eggs or seeds in a single GE crop field. Given the astonishing number of pest individuals exposed to Bt toxins or glyphosate and the large area of agricultural land that utilizes these pesticides, the likelihood of finding rare individuals with the genetic mutation that confers resistance to these pesticides is high. As individuals resistant to a specific pesticide will fare better and increase in numbers compared to the susceptible individuals and if this pesticide is frequently used, resistance management strategies that aim at reducing the selective advantage of resistant individuals are required to thwart resistance evolution and preserve the long-term viability of these widely-used pesticides (Tabashnik, Van Rensburg, and Carrière, 2009).

The use of HR technology simplified weed management tactics to one of applying predominantly glyphosate. The recurrent use of this herbicide over large areas has predictably resulted in a rapid rise in the evolution of glyphosate resistant weeds (Figure 1). At least eight weed species have evolved resistance to glyphosate in fields using glyphosate-resistant crops, and the number is growing (Heap, 2010). For some glyphosate-resistant weeds like Palmer amaranth (*Amaranthus palmeri*) and horseweed (*Conyza canadensis*), estimates indicate that these weeds are present in upwards of 2 million acres and locations where glyphosate-resistant weeds occur are also growing at an increasing rate (National Research Council, 2010). Other weeds that are difficult to manage with glyphosate have also increased in fields of HR crops. This type of weed shift occurs when weeds are tolerant to the conditions found in HR crops—tillage regime, applications of glyphosate—and thus increase in population density and replace less-adapted weeds (Owen, 2008). So far, thirteen such weed species have become more prevalent in weed communities associated with HR corn, cotton and soybeans (Heap, 2010).

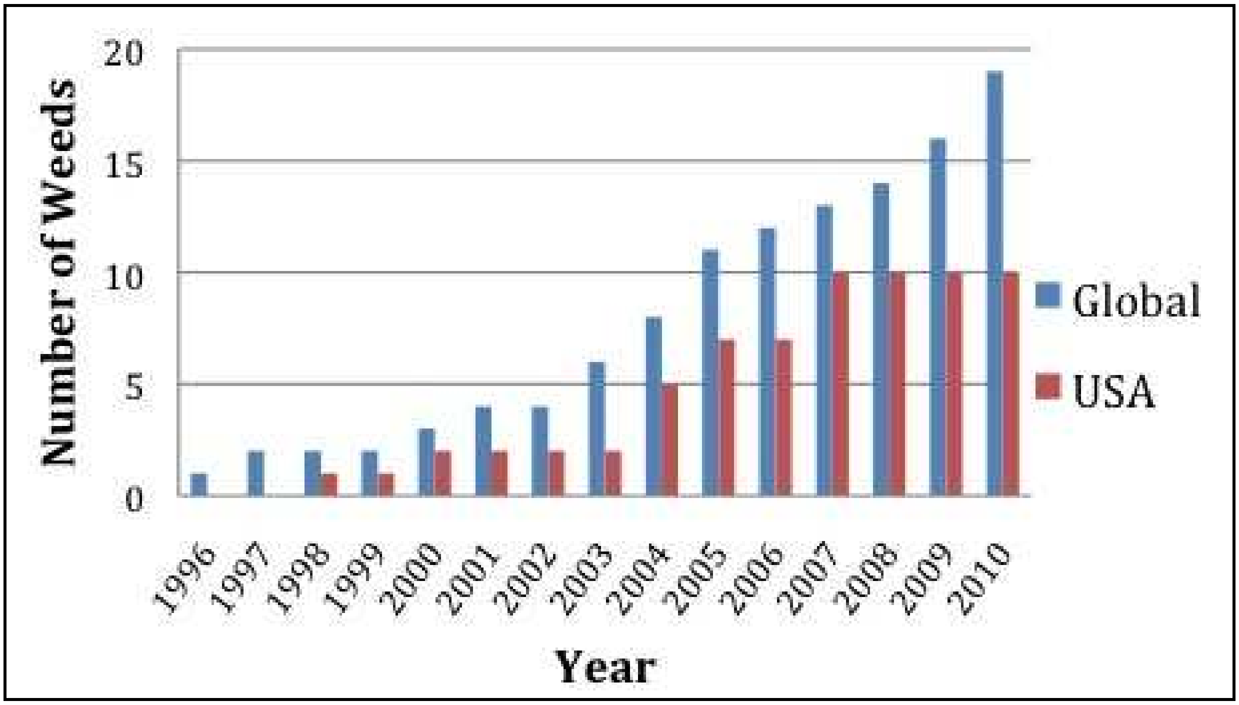

Figure 1. Number of Weed Species That Have Evolved Resistance to Glyphosate. Adapted from http://www.weedscience.org.

Traditional weed management tactics have not been typically used as frequently in HR crops because applying glyphosate is presumed by growers to be simpler, more convenient and faster. Traditional weed management tactics include, but are not limited to: herbicide rotations, sequential herbicide applications, and use of tank-mixes of more than one herbicide. For effective long-term weed management, growers should use herbicides that have different physiological effects, or modes of action, rather than herbicides that kill weeds using the same mechanism. Cultural and mechanical control practices, while effective, are not typically considered in most crop systems due to logistic, environmental and economic concerns. Other effective weed management tactics include sanitation of equipment such as tillage implements and harvesters. While these tactics are effective and can minimize dispersal of HR weeds, growers do not commonly use them.

Commercialization of HR cultivars resistant to more than one herbicide, which will increase in the near future, could facilitate implementation of some of the herbicide-based tactics. Interestingly, greater reliance on glyphosate for weed control has reduced the price of other herbicides and limited efforts to develop new herbicide products. Delaying the evolution of weed resistance to herbicides that are used with HR crops is particularly important in this context because new herbicides are not likely to be readily available in the foreseeable future to replace ones that become ineffective when resistant weed populations evolve. It has been approximately two decades since a new herbicide mechanism of action was discovered and commercialized.

Insect resistance to IR crops has emerged in two insect pest species in the United States. Resistance to Bt toxins linked with increased damage to IR crops in the field has now been documented in four target lepidopteran pests worldwide. While the emergence of insect resistance to IR crops has not been as rapid as the emergence of weeds resistant to glyphosate, a lag time longer than their 15 years of use may be expected before seeing a faster rise in the number of insect species evolving resistance (National Research Council, 2010). The United States Environmental Protection Agency (USEPA) mandates an Insect Resistance Management strategy for some key pests of corn and cotton, whereby refuges—areas where the crop is not IR—are planted to delay the evolution of resistance to Bt toxins. Available data indicate that an abundance of refuges of non-IR host plants is one of the key factors that delay the evolution of resistance. However, levels of compliance to the refuge strategy are declining in some areas of the country, negating the potential for the strategy to delay resistance. At the same time, IR crops with multiple Bt toxins are being introduced and offer an additional strategy of using redundant-killing and decreasing the chances that a pest will evolve resistance to and survive multiple toxins (National Research Council, 2010).

Interbreeding between a crop and close relatives may lead to the movement of GE traits into wild populations and reduce genetic diversity available for future crop improvement or create weed management issues if the close relative has weedy characteristics. In the United States the most widely planted GE crops, corn and soybeans, have no genetically compatible relatives or weedy strains. Other GE crops, including cotton, canola, sugar beets and squash do co-occur on local limited spatial areas with wild relatives, either due to where the crops are planted—canola, squash—or where wild relatives occur as in cotton and sugar beet (National Research Council, 2010).

Some gene flow between sexually-compatible GE and non-GE crops cannot be avoided so that GE and non-GE plants from different fields may cross-pollinate. Because the presence of adventitious GE traits in the non-GE seed supply of canola, cotton, corn, and soybeans is widespread, gene flow also occurs within the same fields when comingling of GE and non-GE seed occurs. Comingling may happen before the production year if adventitious GE traits occur in seed bags due to the seed production process or during the production year if seeds are mixed at planting or if there is germination of seeds left behind from the previous year. High rates of gene flow between GE and non-GE crops could accelerate the evolution of insect pest resistance to IR crops, if many IR plants are routinely present in refuges of non-IR crops. Gene flow between HR and non-HR crops could also increase production costs if gene flow promotes weediness and management problems with volunteer HR crops. Adventitious presence of GE traits in non-GE products can lower the economic value of these products, and thresholds describing acceptable limits for the presence of GE traits in non-GE products have been established in various markets.

The Future Trajectory

HR technology, through the substitution of glyphosate for other herbicides and the complementary adoption of soil conservation practices, has had fewer adverse effects on the environment than the conventional crops replaced. However, the current implementation and use of HR crops has led to the predictable evolution of glyphosate-resistant weeds and other weed shifts, which increasingly have negative economic impacts on farming. Solving this problem will likely include the increased use of herbicides with environmentally undesirable properties and/or more aggressive tillage, which represent shifts in agriculture toward less sustainable practices. IR technology has reduced external applications of insecticides. While insect resistance to Bt toxins has evolved, remedial actions of voluntarily suspending sales of IR seed, commercialization of IR cultivars with new Bt toxins, and targeted use of synthetic insecticides have prevented significant economic consequences attributable to insect resistance.

So far, HR and IR crops that were mainly resistant to glyphosate or produced a single Bt toxin have had neutral or minor—positive or negative—impacts on nontarget organisms. With increasing numbers of HR and IR cultivars commercialized and continued global adoption of GE crops, life science companies can now cross different cultivars to rapidly produce novel GE crop cultivars. It is anticipated that future GE cultivars will be resistant to several herbicides or produce many Bt toxins, which may provide advantages from the perspective of pest resistance management and pest control. The environmental properties of the herbicides and how the use of multiple Bt toxins affect pest and nonpest populations will dictate whether these future GE crops contribute to more environmentally sustainable agricultural practices or not.

Systematic analyses of field-evolved resistance and longer-term research are needed to provide the knowledge required to enhance the durability of current and future generations of GE crops. Because the USEPA has regulatory oversight over IR crops, it actively interacts with relevant stakeholders to develop and mandate resistance management strategies to delay the evolution of insect resistance to Bt. Refuge strategies are tailored to the ecology and genetics of specific pests, so EPA specifies the area, configuration, and types of refuges to be used with particular IR crops. With additional data provided by researchers, farmers and industry, such refuge strategies can evolve. For example, for some cotton pests that feed on many host types, refuges of non-IR cotton are no longer planted in some areas of the country to delay insect resistance to cotton producing two Bt toxins, because it is believed that sufficient other refuges are available.

In contrast to IR crops, HR crops are not regulated as pesticides by EPA. Thus, the management of herbicide resistance is done on a voluntary basis. Given the serious threat for agriculture and the environment posed by glyphosate-resistant weeds and other weed shifts, there is an urgent need for a better dialogue between growers, consultants, researchers, seed companies, and the chemical industry to oversee the development and implementation of weed resistance management strategies for glyphosate and other herbicides, and minimize weeds shifts resulting from use of HR crops in the United States.

At least 15 crop species in the United States have been documented to interbreed with weedy near-relatives (National Research Council, 2010). As more crops on this list are genetically engineered, the potential for negative consequences on weed management may increase, especially for crops like wheat that co-occur with weedy near-relatives over large geographic regions. Similarly, issues about coexistence between GE and non-GE crops will likely increase as more GE crop species are commercialized and additional markets for non-GE products develop.

Fifteen years after commercialization of GE crops in the United States, we still do not completely understand how the intensive use of GE crops can affect the environment compared to other non-GE agricultural production systems. Few studies have provided integrated assessments of the effects of GE crops on ecological services at the landscape scale. HR crops have facilitated and, in the future, will likely continue to influence changes in herbicide use; however, we lack the infrastructure and investment needed to monitor concomitant impacts on the environment such as surface water quality. As new GE crops become available, such as those grown for energy, water or fertilizer conservation, or salt tolerance, the complexity of assessing environmental impacts of these GE crops will undoubtedly increase. Evaluation and monitoring of plant and animal communities, soils, and water, will increase in importance to provide the information needed for developing the most productive and sustainable agricultural systems for the future.

For More Information

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