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Genetically Engineering Crops for a Sustainable Agriculture

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Since the mid-1990s, genetically engineered (GE) crops have swept across the nation's landscape to now cover approximately half of all cropland. While the United States is the undisputed leader in GE crops adoption and use, farmers in many other countries also are adopting them at increasing rates. Despite rapid adoption rates, GE crops have not been without controversy. Depending on the groups to which you listen, GE crops are either the boon or the bane of a more sustainable agriculture. However, those pro and con arguments are often couched in ideological positions and do not reflect the latest natural and social science research findings. This *Choices* theme aims to clarify the complex, also called wicked, issues surrounding the role of GE crops in fostering a more sustainable agriculture and to hopefully elevate the dialogue to a more constructive plane.

A recent National Academy of Sciences meta study aids our task (NRC 2010). The National Research Council convened a multidisciplinary committee in 2008 to assess the impacts of GE crops on farm sustainability in the United States. The members combed the scientific literature to interpret the latest findings and identify the state of peer-reviewed evidence. Importantly, this comprehensive assessment adopted a tripartite sustainability framework of environmental, social and economic effects, which constitute the essential pillars of modern sustainability science. Frequently, arguments and analyses of the role of GE crops in promoting sustainable agriculture neglect the social dimensions. We believe this serious oversight has exacerbated tensions between GE crop proponents and opponents.

The NRC study represents the most thorough look at this fast moving agricultural technology and three articles in this theme summarize and extend the key environmental, economic and social findings. In the end, the NRC assessment could not draw firm conclusions about the sustainability of commercialized GE crops due to critical knowledge gaps. For example, the impacts of the evolving and concentrating seed and chemical industry structure on non-GE seed availability remain largely unexplored and undocumented. Also, large-scale ecological-system analyses of GE-crop plantings have been rare. Many individual studies have been completed, but a cohesive spatial and temporal framework is needed to put the environmental impacts of GE crops, both favorable and unfavorable, into a broader context to evaluate their long-term effects. Finally, researchers have neglected the complex social impacts on adopters and on those who, for whatever reason, chose not to use the technology. Two articles in this issue supplement the NRC assessment to start filling key knowledge gaps. The first by Nag, et al. discusses the driving motivations of academic bioscientists whose discoveries will shape future GE crops. The second by Greene and Smith explores potential ways to manage the coexistence of GE with non-GE crops, a contentious issue in organic circles.

For a variety of technological and economic reasons, the first generation of GE crops has focused mostly on new cost-effective ways to deliver existing pesticides. This accomplishment is not trivial or inconsequential. As the NRC report documents, the available evidence indicates that current GE soybean, cotton, and corn varieties have generally improved the economic and environmental conditions on farms that adopted them compared with using conventional non-GE cropping methods. The substantial but not universal benefits stem mainly from using lower cost, more flexible and more environmentally benign pesticides that complement either no tillage or conservation tillage practices.

Yet, the early favorable effects may not portend enduring improvements, as three articles in this volume explore. Wolfenbarger, Owen and Carrière discuss rapidly spreading weed resistance problems and uncertainties in maintaining the efficacy of the insecticides engineered into insect resistant (IR) crops. If such problems grow, farmers likely will return to more toxic pesticides and more tillage, both of which will partially erode the economic and environmental gains of the GE crops. As Zilberman, Sexton, Marra and Fernandez-Cornejo discuss in their article, GE crops have provided multiple economic benefits to farmers adopting the crops to date, but larger economic questions spawned by global adoption loom. Salient social issues also accompany GE crops, such as reforming R&D institutions to deliver GE crop technologies for minor crops and varieties particularly suited to local needs of producers and consumers, topics explored by Glenna and Jussaume in their article.

Some background may assist readers as they read the articles in this theme. We try to anticipate and answer some questions related to the topics covered.

What are GE Crops?

The most common genetically engineered (GE) traits are of two types. The first produces their own insecticide, reducing crop losses to insect damage, and are termed insect resistant (IR) crops. Most commercial IR crops contain toxins from a soil-dwelling bacterium, *Bacillus thuringiensis* (Bt) that are lethal to the larvae of particular species of moths, butterflies, flies, and beetles (Lepidoptera and Diptera), but are harmless to humans, animals, or types of insects not susceptible to the toxin. The toxins are effective only when a susceptible insect feeds on the plant. The second type is engineered to resist particular herbicides that can be used to kill many types of weeds without harming the crops and are termed herbicide resistant (HR) crops. Most HR seed varieties have been engineered to be resistant to the herbicide glyphosate; the most common herbicide brand utilizing glyphosate is Roundup. Relative to the herbicides it replaced, glyphosate kills most plants without substantial adverse effects on animals or soil and water quality according to the NRC review. Glyphosate can be applied before or after the plant emerges giving the farmer more flexibility in weed control operations. Since 1996, the HR and IR traits have been incorporated into most soybean, corn, and cotton varieties grown in the United States, and accounted for at least 80% or more of soybean, corn, and cotton acreage in the United States in 2009. A few other GE crops with much smaller acreages have been commercialized, including HR versions of canola and sugar beets, IR sweet corn, and virus resistant (VR) varieties of papaya and squash. Not all commercialized GE crops have succeeded, most notably GE tomatoes and potatoes.

What is Sustainable Agriculture?

It is an understatement to say sustainable agriculture is a contested concept. Since discussions about it began in earnest in the 1980s, a plethora of definitions have been proposed. Perhaps the most cited is the U.S. Department of Agriculture definition, codified into law in the 1990 Food, Agriculture, Conservation and Trade Act and reaffirmed in subsequent farm bills. That law defines “sustainable agriculture” as an integrated system of plant and animal production practices having a site-specific application that will, over the long term:

- satisfy human food and fiber needs
- enhance environmental quality and the natural resource base upon which the agricultural economy depends

- make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls
- sustain the economic viability of farm operations
- enhance the quality of life for farmers and society as a whole.

Salient aspects include the integrated system and the inclusion of elements addressing environmental, natural resource, economic and social quality of life dimensions.

Some scientists characterize the concept as emerging from the 'scientific agriculturalist' movement that emphasized diversification, recycling, avoiding chemicals, and decentralized production and distribution. This stands in stark contrast to the 'industrialized agriculture' model of predominant monocropping, heavy use of external chemicals, pesticides and nutrients, and concentration in supply and output markets. Harwood (1990) distills three basic principles that underpin sustainable agriculture:

1. "The interrelatedness of all parts of a farming system, including the farmer and his (sic) family.
2. The importance of the many biological balances in the system.
3. The need to maximize desired biological relationships in the system and to minimize use of material and practices that disrupt those relationships (p.12)."

He explains how these principles can be converted into a plan for action:

- "Agriculture must be increasingly productive and efficient in resource use.
- Biological processes within agricultural systems must be much more controlled from within (rather than by external inputs of pesticides).
- Nutrient cycles within the farm must be much more closed (p.15)."

Note the emphases on developing integrated farming systems, including the farmers, the reliance on localized biological processes, and closing of nutrient cycles.

Are GE crops and sustainable agriculture compatible?

These definitions and frameworks can be used to evaluate the propensity of the current portfolio of GE crops to promote sustainable agriculture. Hubbel and Welsh (1998) developed three scenarios to describe increasing levels of compatibility of GE crops with sustainable agriculture. The first and lowest level is for GE crops that reduce use of the most harmful agricultural chemicals within an agricultural system characterized by monocropping and socio-economic concentration. A prime example would be current HR crops, such as glyphosate resistant. These crops enable the use of a more environmentally benign chemical to control weeds. However, they are external inputs with little farmer control over the development of the technology, are self-limiting because of developing weed resistance and may lead to the loss of efficacy of a relatively benign herbicide in glyphosate. This prospect of resistance development is not unlike that faced by every herbicide and insecticide previously adopted for widespread agricultural use. However, the sheer size of glyphosate-tolerant crop plantings likely has exacerbated the rate of development of weeds resistant to that single chemical.

The second level is comprised of GE crops that help farmers transition away from a chemical-intensive agriculture. IR crops that produce biological insecticides can replace the application of harmful chemicals. The current portfolio of Bt crops exemplifies this second scenario. However, these crops are not fully sustainable because gene flow and pest resistance buildup remain persistent challenges. In some cases, these crops have become parts of integrated pest management approaches, suggesting that they can be used to transition to and even support more biologically complex farming systems (Carriere, Sisterson and Tabashnik, 2004). Yet for the most part, applications of IR crop technologies have promoted a business-as-usual reliance on monocropping or bi-cropping farms and have substituted for some but not all insecticide applications. Therefore IR crops, despite their potential to do so, have not contributed generally to biological complexity or integration of farming systems.

GE crops in the third level would be designed to promote an integrated pattern of sustainable agricultural development. As such, they would maximize the use of natural biological cycles in the farming system, close nutrient cycles within the farm, and reduce the need for external inputs such as fossil-fuel based energy and fertilizers. Potential examples include crops that reduce water requirements, fix part or all of their own nutrients, and stimulate natural plant defenses to pests. To our knowledge, very few GE crop developments fit this description. Ervin, Glenna and Jussaume (2010) add another requirement to this third level, that of addressing socio-economic equity criteria. Such social issues might include making such GE crop innovations accessible to all types of farmers, high resource and low resource, and opening the control of the technology development process to farmer participation.

Populating the third level with seeds that address the full suite of sustainability criteria will require a reframing of the development of GE crops. Such innovative products might be described as meeting the following conditions:

- Engineer traits that mimic ecological processes and natural defenses that confuse, avoid or deter pests or delay or tolerate damage and not rely on the killing of pests through the engineering of toxins into the plant or making the plant able to withstand the application of herbicides.
- Transform the crop to minimize or eliminate transmission of engineered traits through pollen dispersal and other mechanisms.

- Develop GE crops in ways that farmers and other agricultural stakeholders can convey their preferences and knowledge about crop performance and its effects in the supply chain and beyond the farm boundaries.
- Construct intellectual property (IP) arrangements such that farmers can save and replant—but not resell—the seeds to tailor the technologies to their local conditions and shift the locus-of-control of seed production toward the farmer. This approach balances the protection of seed firms' investments with the enhancement of farmer seed acquisition options and increased crop biodiversity.
- Use public support mechanisms to stimulate the development of GE crops that deliver valuable public goods, such as reduced nutrient applications and runoff and renewable energy feedstocks, for which private firms have inadequate incentives to commercialize.
- To reduce regulatory costs, create a differentiated risk assessment and management system that fast tracks GE crop innovations that adhere closely to these sustainability criteria (Ervin and Welsh 2006).

Getting There from Here

Achieving the first two outcomes listed above may require something as concrete as intragenomic changes to the plant, such as switching off certain genes that result in less pest susceptibility, rather than importing genetic material from other species—transgenic transformations. But overall, realizing such a vision of GE crops that support the goals of sustainable agriculture will require major reforms in the private and public R&D institutions guiding GE crops. Let there be no illusion that such massive changes will take time and must proceed incrementally. However, this is a pivotal point in the development and use of GE crops; the first generation of innovations faces some serious challenges, such as weed resistance, which will require diverse approaches to sustain their efficacy. The rising momentum to use GE crops for renewable energy and environmental purposes adds pressure to the R&D agenda. If industry tries to meet the response alone, we can expect more of the same type of GE crop technologies already commercialized. An example is the recent releases of ‘stacked’ varieties with multiple HR or IR traits. These developments may delay the evolution of resistance, but do not address the inherent problems of the pesticide paradigm (Welsh, et al. 2002). Based on sound economics, we should also expect an insufficient response to the public goods issues from industry as they cannot capture enough revenue to provide incentive to invest adequate amounts of R&D.

The NRC report recommends a boost in public research funding to develop GE crops that support more sustainable agricultural systems, as follows:

> *Recommendation 4. Public and private research institutions should be eligible for government support to develop GE crops that can deliver valuable public goods but have insufficient market potential to justify private investment. Intellectual property patented in the course of developing major crops should continue to be made available for such public goods purposes to the extent possible. Furthermore, support should be focused on expanding the purview of genetic-engineering technology in both the private and public sectors to address public goods issues.*

Implementing this recommendation will require a series of steps following the principles of adaptive management. Adaptive management is a structured repeated process of decision making in the face of uncertainty, with an aim of meeting program objectives via active or passive monitoring of outcomes to identify potential problems, and then redirecting resources as necessary. GE crop development, especially a new generation of technologies that follow the vision offered, will be pervaded by uncertainty of many different forms. For example, the best allocation of research support along the basic/fundamental to applied continuum to stimulate the development and commercialization of GE crop technologies that respond to public goods challenges is unknown. This means that the new programs to deliver such innovations will need to follow a "learning by doing" process.

Despite the pervasive uncertainty, several potential policy options can be envisioned that would provide a foundation for such discoveries. Foremost may be the reform of IP mechanisms such that basic and public good science can be widely shared among researchers while applied proprietary discoveries can be protected by patents or other means to give firms incentives to make sufficient investment for commercialization. However, there needs to be strong government oversight of the degree of effective competition in the GE seed industry to foster the breadth of innovation needed. Research has shown clearly that increased concentration in the seed industry stifles such innovation Schimmelpfennig, Pray and Brennan (2004). A final example of needed policy reform is innovative mechanisms to allow farmers to save and replant seeds from GE crops to tailor the crops to the demands of their local ecosystems and crop consumers.

In closing, we should stress that the development of GE crops to sustain and support the whole range of agricultural systems has just begun. As the NRC report documents, GE crops have had substantial impacts on only three crops to date. Yet, U.S. agriculture is a mosaic of several hundred commercial crops, many of which may benefit from the application of GE technology. For a host of reasons, the technology has been applied sparingly to crops that have smaller markets, particularly most specialty crops. Furthermore, the technology has not yet addressed the many potential public goods purposes for which they appeared to hold so much promise a decade ago. Without an infusion of government support and new institutions to increase stakeholder participation in the R&D process, the promise will likely not be fulfilled.

For More Information

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