CHOICES
a publication of AAEA Agricultural & Applied Economics Association
www.ChoicesMagazine.org
2nd Quarter 2010, 25(2)

Genetically Engineering Crops for a Sustainable Agriculture

David Ervin and Rick Welsh
JEL Classification: Q16, Q18, Q24, Q25, Q55, Q56, Q57

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

Carrière Y., M. S. Sisterson, B. E. Tabashnik. (2004). Resistance Management for Sustainable Use of Bacillus thuringiensis Crops. Pp. 65-95 in: *Insect Pest Management: Field and Protected Crops*. A.R. Horowitz, I. Ishaaya (eds.). New York: Springer.

Ervin, D., L. Glenna, and R. Jussaume Jr. (2010). Are biotechnology and sustainable agriculture compatible? *Renewable Agriculture and Food Systems* 25(2): 143-157.

Ervin, D., and R. Welsh. (2006). Environmental effects of genetically modified crops: Differentiated risk assessment and management. Pp. 301-326 in: *Regulating agricultural biotechnology: Economics and policy*. R.E. Just, J.M. Alston and D. Zilberman (eds). New York: Springer Publishers.

Harwood, R. (1990). A history of sustainable agriculture. Pp. 3-19 in: *Sustainable Agricultural Systems*. C. A. Edwards, R. Lal, P. Madden, R. H. Miller, and G. House (eds.). Ankeny Iowa: Soil and Water Conservation Society.

Hubbell, B. and R. Welsh. (1998). Transgenic crops: Engineering a more sustainable agriculture? *Agriculture and Human Values*, 15:43-56.

National Research Council (NRC). (2010). Impact of Genetically Engineered Crops on Farm Sustainability in the United States*. Washington, DC: National Academies Press.*

Schimmelpfennig, D., C. E. Pray, M. F. Brennan. (2004). The impact of seed industry concentration on innovation: a study of US biotech market leaders. *Agricultural Economics* 30: 157–167.

Welsh, R, B. Hubbell, D. Ervin and M. Jahn. (2002). GM crops and the pesticide paradigm [correspondence]. *Nature Biotechnology 20: 548-549.*

Welsh, R. and L. Glenna. (2006). Considering the role of the university in conducting research on agri-biotechnologies. *Social Studies of Science*. 36: 929-942.

David Ervin (dervin@pdx.edu) is a Professor of Economics and Environmental Management and a Fellow in the Center for Sustainable Processes and Practices at Portland State University in Portland, Ore. Rick Welsh (welshjr@clarkson.edu) is a Professor of Social Science at Clarkson University in Potsdam, N. Y.

The authors acknowledge helpful comments from Walt Armbruster and LaReesa Wolfenbarger.

CHOICES
a publication of AAEA
Agricultural & Applied Economics Association
www.ChoicesMagazine.org
2nd Quarter 2010, 25(2)

Environmental Opportunities and Challenges of Genetically-Engineered Crops

L. LaReesa Wolfenbarger, Micheal D. K. Owen, and Yves Carrière
JEL Classifications: Q16, Q18, Q24, Q25

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).

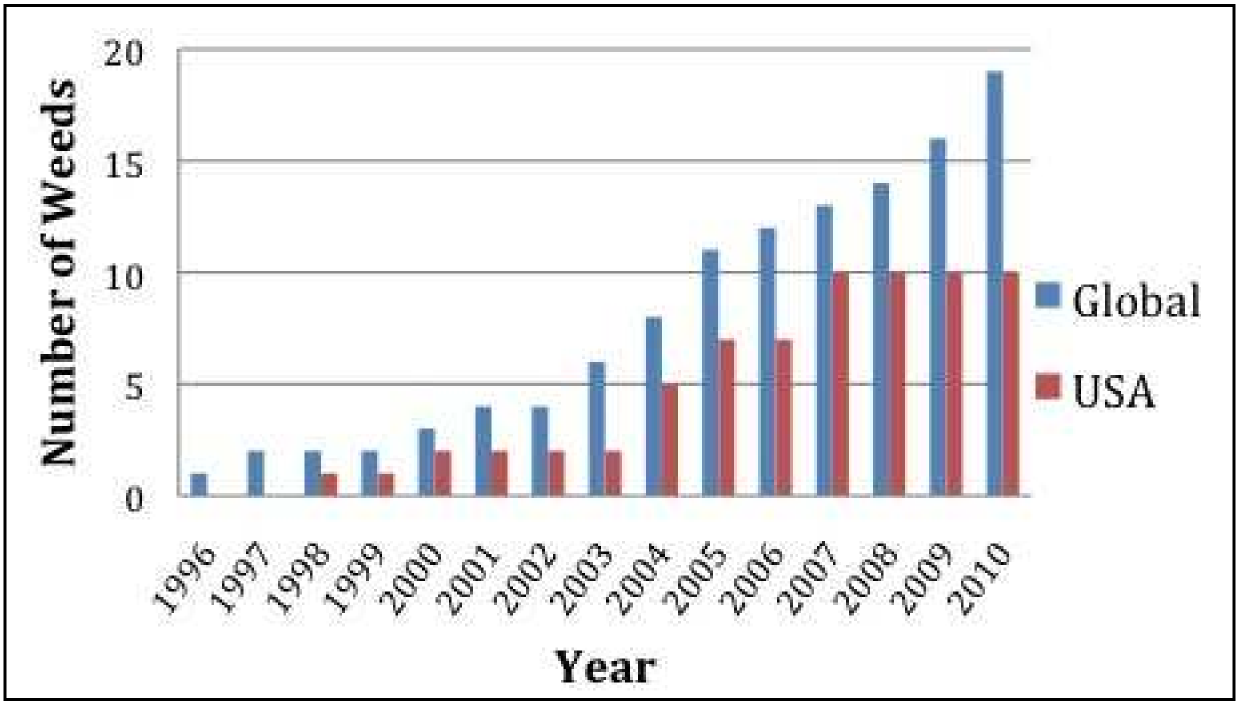


Figure 1. Number of Weed Species That Have Evolved Resistance to Glyphosate. Adapted from http://www.weedscience.org.

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

Berwald, D., Matten, S., and Widawsky, D. (2006). Economic analysis and regulating pesticide biotechnology at the U.S. Environmental Protection Agency. Pp. 1-15 in *Regulating Agricultural Biotechnology: Economics and Policy*, eds., Just, R. E., Alston, J. M., and Zilberman, D. New York, NY: Springer Science + Business Media.

Carrière Y., Crowder, D. W., and Tabashnik, B. E. (2010). Evolutionary ecology of adaptation to Bt crops. *Evolutionary Applications*, doi:10.1111/j.1752-4571.2010.00129.x.

Cerdeira, A.L., and Duke, S.O. (2006). The current status and environmental impacts of glyphosate-resistant crops; a review. *Journal of Environmental Quality, 35*, 1633-1658.

Dorhout, D. L., and Rice, M. E. (2010). Intraguild competition and enhanced survival of western bean cutworm (Lepidoptera: Noctuidae) on transgenic Cry1Ab (MON810) *Bacillus thuringiensis* corn. *Journal of Economic Entomology, 103*, 54-62.

Heap, I. (2010). *International survey of herbicide resistant weeds.* Available online: http://www.weedscience.org.

National Research Council. (2010). *The impact of genetically engineered crops on farm sustainability in the United States.* Washington, D.C.: The National Academies Press.

Owen, M. D. K. (2008). Weed species shifts in glyphosate-resistant crops. *Pest Management Science, 64*, 377-387.

Powles, S. B. (2008). Evolved glyphosate-resistant weeds around the world: lessons to be learnt. *Pest Management Science, 64*, 360-365.

Tabashnik, B. E., Van Rensburg, J. B. J., and Carrière, Y. (2009). Field-evolved insect resistance to Bt crops: definition, theory, and data. *Journal of Economic Entomology, 102*, 2011-2025.

Wolfenbarger, L. L., Naranjo, S., Lundgren, J., Bitzer, R., and Watrud, L. (2008). Bt crop effects on functional guilds of non-target arthropods: a meta-analysis. *PloS One 3*, Article Number e2118.

Yves Carrière (ycarrier@ag.arizona.edu) is a Professor of Insect Ecology, University of Arizona, Tucson, Arizona. Micheal D. K. Owen (mdowen@iastate.edu) is a Professor of Agronomy, Iowa State University, Ames, Iowa. L. LaReesa Wolfenbarger (lwolfenbarger@unomaha.edu) is an Associate Professor of Biology, University of Nebraska at Omaha, Omaha, Nebraska.

CHOICES
a publication of AAEA
Agricultural & Applied Economics Association

www.ChoicesMagazine.org

2nd Quarter 2010, 25(2)

The Economic Impact of Genetically Engineered Crops

David Zilberman, Steve E. Sexton, Michele Marra, and Jorge Fernandez-Cornejo
JEL Classifications Q160, Q240, Q420

Since the 1990s, genetic plant engineering has yielded a variety of applications for agricultural production, including traits intended to improve the shelf-life of produce, improve crop nitrogen fixation, and bolster control of agricultural pests. However, only two traits achieved commercial success. One trait confers insect resistance (IR) to crops by programming the crop plant to produce a naturally occurring chemical that is toxic to common insects. The other trait confers herbicide-tolerance (HT) and permits farmers to spray broad-spectrum chemicals to kill weeds without killing the crop plant. These traits have been widely adopted in production of corn, canola, cotton, and soybean.

The adoption of genetically engineered (GE) crops has significantly affected the economics of these crops and the welfare of farmers and consumers. It has also had spillover effects on other crops and markets. In this paper, we present findings of economic research on the impacts of GE crops at the farm level, factors that explain their adoption, impacts on prices, and effects on welfare of various segments in the economy. We rely on the findings of a new and thorough report by the National Research Council (NRC) (2010), a recent survey of agricultural biotechnology by Qaim (2009), and a new study by Sexton and Zilberman (2010).

The Impact of GE Crops at the Farm Level

A starting point for analyzing the impact of IR traits is the damage control function approach of Lichtenberg and Zilberman (1986). Actual crop output is given to be equal to potential output minus pest damage. Damage can be controlled by a variety of pest control techniques, including pesticides, cultural practices, and GE traits. By controlling pest damage, IR traits boost actual crop output and improve crop yields. The increase in yields due to the adoption of IR traits is expected to be small on farms that use the GE trait to substitute for chemical pest control applications. The effects will be larger where chemicals and other damage control approaches did not effectively control pest damage. Thus, developing countries, in which chemicals are not widely used, should benefit the most from IR technologies. Even in developed countries, however, where IR traits largely substitute for other effective control approaches, the costs associated with damage control, including pecuniary costs, environmental costs, and effort, decline.

The magnitude of yield gains associated with IR crop adoption also depends on the quality of the seed germplasm into which the IR trait is inserted. Since the Green Revolution, seed companies have bred high-yield seed varieties that are tailored to the specific agronomic conditions of heterogeneous farming regions. IR traits are not inserted into the best germplasm in all locations. If farmers must abandon a local seed cultivar in order to adopt an IR trait that is only available in a generic seed, then some yield loss may mitigate the yield gains associated with the damage control capabilities of the IR trait. This yield loss is called yield drag.

The NRC (2010) reported that adoption of IR crops throughout the United States resulted mostly in modest increases in yield and significant savings in pesticide costs. Yield drag was not evident. As Table 1 from Qaim (2009) showed, IR seeds that produce the naturally occurring toxin *Bacillus thuringiensis* (Bt), generally have much larger yield effects in developing countries than in developed countries. Bt cotton, adopted extensively in developing countries, has exhibited particularly large yield gains. In countries where the yield effects of Bt cotton adoption were modest, like China, Bt crop adoption has caused dramatic declines in pesticide use. Qaim (2009) also reports significant reductions in pesticide-related accidents and deaths associated with IR crop adoption.

Table1. Average Farm Level Agronomic and Economic Effects of Bt Crops

Country	**Insecticide reduction (%)**	**Increase in effective yield (%)**	**Increase in gross margin (US$/ha)**
		Bt cotton	
Argentina	47	33	23
Australia	48	0	66
China	65	24	470
India	41	37	135
Mexico	77	9	295
South Africa	33	22	91
USA	36	10	58
		Bt corn	
Argentina	0	9	20
Philippines	5	34	53
South Africa	10	11	42
Spain	63	6	70
USA	8	5	12

Source: Qaim, M., 2009.

While Qaim (2009) and NRC (2010) mostly presented results of studies that were done in the period between 2000 and 2006, the study by Sexton and Zilberman (2010) covers the period between 1996 and 2008. Based on a global survey of GE crop use, it shows that IR traits have had a much bigger yield effect than HT traits, especially in developing countries. The study suggests that in some countries soybean yield per acre might have been declining because of soybean expansion made possible by the elimination of late season weeds. But some of this expansion was not associated with increasing agricultural acreage per se. For example, much of the massive expansion in soybean acreage in Argentina was due to adding soybean as a second crop in a multiple cropping system. This adoption of double-cropping is possible with HT soybean because fallow periods between crops are reduced with use of less toxic chemicals and improved control of late season weeds.

While there is ample evidence that IR crops generally lead to higher yields, it is less clear that HR traits boost yields. Table 2 summarizes existing literature on HT yield effects. A number of studies find that there are no yield gains due to HT adoption, while others find that small yield gains accompany HT crop adoption. Fernandez-Cornejo, Klotz-Ingram, and Jans (2002), for instance, found on the basis of a national farm-level survey that HR soybean had a small advantage in yield over conventional soybean, likely because of better weed control.

Table 2. Summary of Primary Studies on the Effects of Herbicide Resistant (HR) Crops on Yields

Crop/Researchers/ Date of Publication	**Data Source**	**Effect on Yields**
Herbicide-tolerant soybeans		
Delannay et al., 1995	Experiments	Same
Roberts et al., 1998	Experiments	Increase
Arnold et al., 1998	Experiments	Increase
Marra et al., 1998	Survey	Increase
Fernandez-Cornejo et al., 2002[1]	Survey	Small increase
Duffy, 2001	Survey	Small decrease
Marra et al., 2004	Survey	Same
Bernard et al., 2004	Survey	Increase
Qaim and Traxler, 2005	Survey	Same
Herbicide-tolerant cotton		
Vencil, 1996	Experiments	Same
Keeling et al., 1996	Experiments	Same
Goldman et al., 1998	Experiments	Same
Culpepper and York, 1998	Experiments	Same
Fernandez-Cornejo et al., 2000[1]	Survey	Increase

Sources: Fernandez-Cornejo and Caswell, 2006; Bernard, Pesek, and Fan, 2004; and Qaim and Traxler, 2005.

In contrast, a national survey of soybean producers in 2002 found that there was no statistical difference in yield between conventional soybean and HR soybean (Marra, Piggott, and Carlson, 2004). Yet another study based on a mail survey of Delaware farmers in 2001 found that HR soybean had a three-bushel-per-acre yield advantage over conventional soybean (Bernard, Pesek, and Fan, 2004).

Whereas theory predicts IR traits will boost yields, the nature of HT traits suggests they will make damage control cheaper and easier, but not necessarily boost yields. HT traits permit the substitution of broad-spectrum glyphosates like Monsanto's Round-Up for more targeted, toxic and expensive chemicals that can kill specific weed species and leave crop plants intact. HT traits, therefore, do not constitute a new mechanism for damage control the way IR traits do. To make use of HT traits, farms must employ much of the same capital in weed control as is used with conventional seed. IR traits, on the other hand, require little capital and can substitute for chemical applications all together. To the extent HT traits reduce the costs of chemical applications, they may cause an increase in the use of chemical control, which can lead to yield gains as damage declines.

The NRC (2010) suggested that the adoption of IR and HT crops has a wide variety of benefits in addition to the immediate yield and cost-saving effects. Both traits can improve harvesting efficiency. IR crop reduces demand for inputs used in pestide applications, including machinery, fuel and water. The use of HT traits has led to increased adoption of no-tillage systems, which requires some modifications of equipment, but tends to significantly reduce fuel expenditures and effort, as well as reducing soil erosion. There are several studies that identify improved product quality and reduced damage in storage (NRC, 2010). Reduced yield risk associated with GE crops has affected farmers' need for insurance, and there is evidence that adopting farmers are receiving insurance premium discounts and gaining access to improved options for managing risks.

The benefits of GE crop adoption come at a price. Seed prices have increased with the introduction of GE technologies, and the share of seed prices in overall production costs has increased. Relative to 1994, seed prices have risen by 140% while the index of other input prices has increased by 80%. The highest price increase in the United States has been in cotton.

Many of the commercially available GE products have proven profitable to U.S. farmers, accounting for yield, cost, and other monetary effects. Furthermore, several studies document that nonpecuniary benefits to farmers were important causes for adoption of GE varieties (NRC, 2010). They include reduced management effort and work time, equipment savings, improved operator and worker safety, improved environmental safety, and total convenience (Marra and Piggott, 2006). These effects were not consistent and varied by location, but overall they are confirmed with evidence that GE crops save managerial time because of the associated simplicity and flexibility of pest control that they provide (Fernandez-Cornejo, Hendricks, and Mishra, 2005). As the NRC report recognized, standard measures of farm profits, such as net returns to management, give an incomplete picture of economic returns because they usually exclude the value of management time itself. However, recent studies show that adoption of management-saving technologies such as HR soybeans frees operators' time for off-farm employment, which leads to higher off-farm income (Fernandez-Cornejo, Hendricks, and Mishra, 2005; Gardner, Nehring, and Nelson, 2009).

Market Effects

Theory suggests that GE crops boost agricultural supply to the extent they boost farm yields. But by reducing damage and damage control costs, GE traits can also make it profitable to farm marginal land that cannot be profitably farmed with conventional seeds. Changes in supply affected commodity prices and, indirectly, the well-being of farmers and other sectors in the economy. There is a large body of literature that estimated the impact of GE varieties on commodity prices. Most of the studies reviewed by the NRC (2010) considered the early years of agricultural biotechnology adoption, when adoption rates were low. They found modest reductions in commodity prices of less than 2%. Over time, the effect of GE traits on crop prices may be higher—as much as 4%. The study by Sexton and Zilberman (2010), which considers global effects of GE traits, suggested price effects that are more substantial—greater than 10% in the case of cotton. Their analysis provides other evidence supporting the substantial effect of GE crops on commodity prices. The demand for soybean soared during the last 10 years with a growing demand for meat in Asian countries, especially China. The twofold expansion of soybean acreage around the world, largely due to HT soybean adoption, contributed to a large expansion of supply that was capable of meeting this growing demand with modest impact on prices. Similarly, cotton was a crop with the highest rate of overall adoption globally—90% adoption of Bt cotton in India—and the highest yield effect. Cotton was the only major crop that did not experience the agricultural commodity price inflation of 2007/2008, whereas staple crops for which GE traits were not available, like wheat and rice, experienced the highest price increases.

Several studies have investigated the distributional impact of the adoption of GE crops. These results appear in Table 3. Most of the studies suggested an overall gain from the adoption of these crops, but the distribution of benefits varies (NRC, 2010). The gain to farmers varies from 5% to 40%, depending on the price and yield effects, as well as the cost of the seed. The innovators captured between 10% and 70% of the benefits. Most studies found that they captured around 40%. The share of benefits to U.S. consumers varies from 6% to 60%, and the share of benefits captured by consumers in the rest of world also varies from 6% to more than 30%. The differences in outcomes reflect the heterogeneous effects of different types of seed innovations. The share of benefits accruing to consumers is likely to be greater for GE crops that benefit from larger yield gains characterized by very inelastic demand—that is, a small increase in supply reduces prices substantially. On the other hand, when the adoption of GE varieties mostly leads to substitution from chemical pesticides to GE varieties without significant changes in supply, much of the benefit will be captured by the farmers and the seed companies.

Most of the studies that analyzed the distributional effects of GE crops were undertaken early in the life of GE varieties. The result of the study by Sexton and Zilberman (2010) suggests that as the price effect of GE varieties increases because of increased adoption, the gain to consumers from their introduction becomes much more substantial.

Table 3. Benefits of the Adoption of Genetically Engineered Crops and Their Distribution

Study	**Year**	**Total benefits ($ million)**	**Share of total benefits (%)**			
			U.S. farmers	**Innovators**	**U.S. consumers**	**Net ROW**
Bt cotton						
Falck-Zepeda et al. (1999)	1996	134	43	47	6	
Falck-Zepeda et al. (2000a)	1996	240	59	26	9	6
Falck-Zepeda et al. (2000b)	1997	190	43	44	7	6
Falck-Zepeda et al. (1999)	1998	213	46	43	7	4
Frisvold et al. (2000)	1996–1998	131–164	5-6	46	33	18
US-EPA (2001)[a]	1996–1999	16–46	NA	NA	NA	NA
Price et al. (2003)	1997	210	29	35	14	22
Herbicide-resistant cotton						
Price et al. (2003)	1997	232	4	6	57	33
Herbicide-resistant soybean						
Falck-Zepeda et al. (2000b)	1997-LE[b]	1,100	77	10	4	9
	1997-HE[c]	437	29	18	17	28
Moschini et al. (2000)	1999	804	20	45	10	26
Price et al. (2003)	1997	310	20	68	5	6
Qaim and Traxler (2005)	1997	206	16[d]	49	35	NA[e]
Qaim and Traxler (2005)	2001	1230	13[d]	34	53	NA[e]

NA = not applicable; ROW = rest of the world (includes consumers and producers).
[a]Limited to U.S. farmers.
[b]LE = low elasticity; assumes a U.S. soybean supply elasticity of 0.22.
[c]HE = high elasticity; assumes a U.S. soybean supply elasticity of 0.92.
[d]Includes all soybean producers.
[e]Included in consumers and producers.

Source: NRC, 2010.

The Sexton and Zilberman study actually suggests that the price increases that would have occurred without the introduction of GE crops are of the same magnitude as the price effect associated with the diversion of corn, soybean, and other crops to produce biofuel between 2006 and 2008.

The NRC (2010) study found that producers of field crops gained overall from the introduction of GE varieties, but these gains are the net effect of higher yield, lower cost, and lower commodity prices. On the other hand, livestock producers in the United States and around the world have significantly benefited from the adoption of GM varieties. There is evidence that the nutritional characteristics of GE and conventional cultivars of soybean and corn are similar, and since feed consists of 50% of the cost of livestock production, livestock operators benefited from the reduction of commodity prices associated with the introduction of GE crops. They also benefited from increased feed safety with the reduction of mycotoxins in GE varieties.

The adoption of GE crops affected non-GE farmers as well. The introduction of Bt traits reduced the demand for and thus the price of insecticides that Bt replaced. The introduction of HT traits, on the other hand, increased the demand and thus the price of the herbicides that are used with these cultivars. There is some evidence that more effective control of pest damage associated with adoption of IR cultivars may reduce pest damage to neighboring crops that share the same pest population.

GE adoption also presents risk of gene transfer to neighboring non-GE crops and comingling of output, which imposes risk on nonadopting farmers. The regulatory constraints on use of GE traits may result in substantial economic impact when the traits are not used appropriately. One example is the case of Starlink, a GE corn hybrid that was approved for animal consumption but was mistakenly comingled with corn used for human consumption. This mistake resulted in significant penalties to the firm and fueled doubts about traceability and food safety. There is evidence that gene flow from GE cultivars resulted in mixing of some GE cultivars with non-GE cultivars (NRC, 2010).

To the extent that buyers establish strict standards on purity in purchasing non-GE crops, there can be substantial costs to non-adopters of gene flow from GE to non-GE varieties. Costs of preventing comingling and gene flow can also be substantial, and include the costs of extra screening and segregation of output throughout the supply chain, which can require redundant operations. Organic farmers may be especially vulnerable to such gene flow in cases where they operate under conditions of zero tolerance. More research is needed to understand some of the side effects of GE varieties on non-GE farmers. Improvements in technologies for tracing and separating commodities can enhance food safety and improve performance of supply chains, enabling more beneficial coexistence between GE and non-GE producers.

Future Prospects

GE crops are still in their infancy. Thus far, there is evidence that U.S. farmers who adopted these crops experienced lower costs of production and/or obtained higher yields. They also gained from substantial nonmonetary benefits. Overall, GE crops seem to improve farm profitability while also reducing commodity prices to the benefit of consumers. However, while rates of adoption of GE varieties in corn, soybean, and cotton have been dramatic in some countries, regulatory constraints have limited the spread of the technologies across the globe and thus diminished their benefits. The commodity price inflation of 2007/2008, the increased investment in biofuels, growing populations around the world, and the concern about greenhouse gas emissions suggest that an increase in agricultural productivity is essential. GE crops are one technology that can contribute to productivity gains.

The adoption of GE traits to control pests has been considerable in a small number of critical crops over the last 15 years. It has already made a major difference in increasing productivity, reducing food prices, and improving environmental quality. Yet, while the investment in new varieties grew steadily in the 1990s, it contracted significantly in 1999, the year the European Union instituted a de facto ban on GE technologies (Graff, Zilberman, and Bennett, 2009). In the last decade, we have seen a relative slowdown in the introduction of new GE varieties in spite of the dramatic expansion of land planted to the initial GE varieties. As the NRC (2010) suggested, there are hundreds of new traits in the pipeline, at various stages of development. These traits may contribute to improving food quality, especially feed quality, enhancing shelf life, and increasing drought tolerance.

The capacity to expand the utilization of GE technologies and fully take advantage of the potential of GE traits in agriculture requires continuous investment in research and an economic and regulatory environment that will foster development of new GE varieties. Further research is needed to understand the economics of the biotechnology industry and how it is affected by regulations and incentives. This may help to further improve the regulatory environment and generate conditions under which GE technologies can provide greater welfare improvements and promote environmental sustainability.

For More Information

Bernard, J.C., Pesek Jr., J.D., and Fan, C. (2004). Performance results and characteristics of adopters of genetically engineered soybeans in Delaware. *Agricultural and Resource Economics Review*, 33(2), 282-292.

Falck-Zepeda, J.B., Traxler, G., and Nelson, R.G. (1999). Rent creation and distribution from the first three years of planting Bt cotton. ISAAA Briefs No. 14. Ithaca, N.Y.: The International Service for the Acquisition of Agri-biotech Applications (ISAAA).

Falck-Zepeda, J.B., Traxler, G., and Nelson, R.G. (2000a). Surplus distribution from the introduction of a biotechnology innovation. *American Journal of Agricultural Economics,* 82(2), 360-369.

Falck-Zepeda, J.B., Traxler, G., and Nelson, R.G. (2000b). Rent creation and distribution from biotechnology innovations: The case of Bt cotton and herbicide-tolerant soybeans in 1997. *Agribusiness,* 16(1), 21-32.

Fernandez-Cornejo, J., and Caswell, M.F. (2006). The first decade of genetically engineered crops in the United States. Economic Information Bulletin No. 11. Washington, D.C.: U.S. Department of Agriculture, Economic Research Service, April.

Fernandez-Cornejo, J., Klotz-Ingram, C., and Jans, S. (2002). Farm-level effects of adopting herbicide-tolerant soybeans in the U.S.A. *Journal of Agricultural & Applied Economics,* 34(1), 149-163.

Fernandez-Cornejo, J., Hendricks, C., and Mishra, A. (2005). Technology adoption and off-farm household income: The case of herbicide-tolerant soybeans. *Journal of Agricultural and Applied Economics,* 37(3), 549-563.

Frisvold, G.B., Tronstad, R., and Mortensen, J. (2000). Adoption of Bt cotton: Regional differences in producer costs and returns. In 2000 proceedings of the beltwide cotton conferences, eds. P. Dugger and D. Richter. Memphis, TN: National Cotton Council, pp. 337-340. Available online: http://www.scopus.com/inward/record.url?eid=2-s2.0-0033810558&partnerID=40.

Gardner, J.G., Nehring, R.F., and Nelson, C.H. (2009). Genetically modified crops and household labor savings in US crop production. *AgBioForum*, *12*(3&4), 303-312.

Graff, G.D., Zilberman, D., and Bennett, A.B. (2009). Correspondence: The contraction of agbiotech product quality innovation. *Nature Biotechnology,* 27 (8), 702-704.

Lichtenberg, E., and Zilberman, D. (1986). The econometrics of damage control: Why specification matters. *American Journal of Agricultural Economics*, 68(2), 262-273.

Marra, M.C. 2001. Agricultural biotechnology: A critical review of the impact evidence to date. In *The future of food: Biotechnology markets and policies in an international setting*, ed. P.G. Pardey. Washington, D.C.: International Food Policy Research Institute, pp. 155-184.

Marra, M., and Piggott, N. (2006). The value of non-pecuniary characteristics of crop biotechnologies: A new look at the evidence. In *Regulating agricultural biotechnology: Economics and policy, natural resource management and policy*, Vol. 30, eds. R.E. Just and J.M. Alston. New York: Springer, pp. 145-178.

Marra, M., Piggott, N.E., and Carlson, G.A. (2004). The net benefits, including convenience, of Roundup Ready® soybeans: Results from a National Survey. Raleigh, NC: NSF Center for IPM Technical Bulletin 2004-3.

Moschini, G., Lapan, H., and Sobolevsky, A. (2000). Roundup Ready® soybeans and welfare effects in the soybean complex. Agribusiness, 16(1), 33-55.

National Research Council. (2010). *Impact of Genetically Engineered Crops on Farm Sustainability in the United States.* Committee on the Impact of Biotechnology on Farm-Level Economics and Sustainability. Washington, D.C.: The National Academies Press.

Price, G.K., Lin, W., Falck-Zepeda, J.B., and Fernandez-Cornejo, J. (2003). Size and distribution of market benefits from adopting biotech crops. TBN-1906. Washington, D.C.: U.S. Department of Agriculture.

Qaim, M. (2009). The economics of genetically modified crops. *Annual Review of Resource Economics,* 1, 665-693.

Qaim, M., and Traxler, G. (2005). Roundup Ready® soybeans in Argentina: Farm level and aggregate welfare effects. Agricultural Economics, 32(1), 73-86.

Sexton, S., and Zilberman, D. (2010). *The economics of agricultural biotechnology adoption: Implications for biofuel sustainability*. Presented at the NBER Agricultural Economics Conference, Cambridge, Mass.

U.S. Environmental Protection Agency. (2001). Biopesticides registration action document - Bacillus thuringiensis plant-incorporated protectants. Washington, D.C.: U.S. Environmental Protection Agency/Office of Pesticide Programs/Biopesticides and Pollution Prevention Division. Available online: http://www.epa.gov/oppbppd1/biopesticides/pips/bt_brad.htm.

David Zilberman (zilber11@berkeley.edu) is Professor and Robinson Chair, Department of Agricultural and Resource Economics, University of California at Berkeley, Berkeley, California. Steven E. Sexton (ssexton@berkeley.edu) is a PhD candidate, Department of Agricultural and Resource Economics, University of California at Berkeley, Berkeley, California. Michele Marra (michele_marra@ncsu.edu) is Professor, Department of Agricultural and Resource Economics, North Carolina State University, Raleigh, N.C. Jorge Fernandez-Cornejo (JORGEF@ers.usda.gov) is Agricultural Economist, Economic Research Service, USDA, Washington, D.C.

David Zilberman is a member of the Giannini Foundation of Agricultural Economics. Some of the research leading to this study was supported by the Energy Biosciences Institute and the USDA.

The views expressed are those of the authors and do not necessarily correspond to the views or policies of the USDA.

CHOICES
a publication of AAEA
Agricultural & Applied Economics Association
www.ChoicesMagazine.org
2nd Quarter 2010, 25(2)

Social Equity and the Genetically Engineered Crops Controversy

Leland L. Glenna and Raymond A. Jussaume Jr.
JEL Classification: Y80

Over a decade since the first genetically engineered (GE) crops were approved, an increasingly polarized debate regarding whether GE crops could promote agricultural sustainability shows no signs of ebbing. Proponents emphasize the potential of this technology to enhance agricultural production with the possibility of reducing the use of economically costly and environmentally detrimental inputs, as well as the potential to address challenges related to changing climatic conditions. Critics counter with concerns that include the risks associated with releasing novel life forms into the natural environment, the increasing concentration of economic power in the small number of firms that control important intellectual property, the possible continued decrease in farm numbers, and other ethical issues associated with manipulation and control of life forms. Proponents and critics alike employ the vocabulary of sustainability to frame their arguments, including concerns about the long-term well-being of humankind. They also often refer to the same scientific research to support their assertions. This suggests to us that the differing views over whether GE crops can contribute to agricultural sustainability have roots in the way sustainability is conceptualized and used to evaluate the impacts of GE crops.

A major contributing factor to the conflicting viewpoints is that proponents and critics alike generally ignore the social equity issues inherent in the concept of sustainability (Lacy, et al. 2009). When scholars do address social impacts, they tend to rely on simplistic assumptions about the social relations that enable or constrain the emergence of sustainable practices and ignore the salient social issues surrounding the development and diffusion of a technology (Ervin, Glenna, and Jussaume, 2010). This oversight is disappointing given that attention to social issues is widely considered to be an essential element in virtually all definitions of sustainability, although there are certainly differences in the social issues that are identified and how they are defined. The long history of social scientific research on the role of technology in processes of social change and adaptation further reveals the importance of recognizing the necessity to incorporate social equity in investigations of any technology's economic, social, political, and environmental impacts. Such assessments are necessary for identifying the potential risks and benefits associated with technology adoption, and thus to generate a holistic analysis of a technology's sustainability potential.

Our goal is to highlight the centrality of the social dimension of the concept of sustainability, with a particular emphasis on social equity. We utilize the definition of social equity offered by the World Bank in *World Development Report 2006: Equity and Development*, which states that "...individuals should have equal opportunities to pursue a life of their own choosing and be spared from extreme deprivation in outcomes." We examine social contexts that enable or constrain opportunities for various actors at multiple levels: agribusiness and industry, national and international policy makers, farmers and their local communities, and the university and academic scientists. We then identify key social innovations necessary for enabling GE crops to become part of a sustainable agricultural system.

Sustainability

The concept of sustainability had its origins in renewable natural resource management over a century ago. The concept has been embraced in recent years as part of a movement that seeks to advocate for development that moves beyond the simple goals of economic growth and incorporates concerns for environmental impacts and social welfare. The 1987 Brundtland Commission popularized sustainability on a global scale. However, many have pointed out that the concept remains vague and misunderstood.

The malleability of the concept of sustainability has been evident in debates surrounding agricultural sustainability. Research indicates that, during congressional hearings leading to the 1985 Food Security Act, at least four distinct definitions of sustainable agriculture emerged. Those definitions included sustaining the conventional agricultural system, sustaining small-farm livelihoods, sustaining the natural resource base of agriculture, and a hybrid approach that emphasized sustaining farm livelihoods and the natural environment (Glenna 1999).

Despite the vague and contested nature of efforts to apply the concept of sustainability to policy debates and to advocate for particular technologies, it is important to remember that conceptualizations of sustainability have long emphasized social, economic, and ecological factors in a holistic and integrated approach. Most definitions of sustainability, including the Brundtland Report, make explicit references to the importance of social equity. In fact, such concerns were codified into law in the 1990 Food, Agriculture, Conservation, and Trade Act. To be sustainable, according to the law, agriculture must:

- “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 and enhance the quality of life for farmers and society as a whole."

This definition of sustainability emphasizes that economic, ecological, and social factors, including the quality of life for farmers and society as a whole, must be managed in an integrated fashion if the agrifood system is to be sustainable.

Unfortunately, the growing popularity of the use of the term sustainability has not contributed to a marked increase in thinking about change holistically and as a process. Thus, assessments of GE crops often focus on economic utility for actors such as farmers, consumers or firms, or impacts on specific environmental dimensions, such as water quality or beneficial pest populations. Such assessments often disregard interactions between the economic, environmental, and the social. More importantly for our paper, social concerns, including whether the costs and benefits of specific applications of GE technology are shared equitably across all classes of farmers and their communities, consumers and firms, are often left unaddressed altogether. An analytical focus exclusively on economic sustainability or environmental sustainability undermines the integrated perspective that thinking about sustainability is meant to encourage.

As noted in the National Research Council's 2010 report, *Impact of Genetically Engineered Crops on Farm Sustainability in the United States*, social issues associated with the development and dissemination of GE crops, including questions of equity, have been grossly understudied. And analyses of social, economic, and ecological interactions associated with GE crops have not been common. When efforts are made to integrate multiple concerns, the social and economic dimensions are often so oversimplified that the arguments do more to obscure than illuminate. For example, increasing yield is commonly presented as an unmitigated social benefit. What is often overlooked is how higher yields do not necessarily guarantee improved economic farm viability or decreased hunger. Increasing production in a context of chronic overproduction can lead to lower prices for farmers. And lower food prices do not necessarily benefit those who do not have the income to purchase food—a “lack of effective demand”.

A *New York Times* article, “India’s Poor Starve as Wheat Rots,” described how 350 million people in India went hungry as crops rotted in the field and as crops from past years sat untouched in granaries. Such occurrences have been common since the first modern famine, the Irish potato famine of the 1840s, when a fungus decimated the primary food source for the tenant farmers in Ireland. During the famine, Ireland continued to export foodstuffs. The problem, in other words, was not a lack of agricultural commodity production. The problem was a lack of social equity: the productive land was owned by a few who exploited poor tenant farmers to produce commodities for export while a free-market ideology paralyzed the political will to solve the problem. A similar problem continues today. Famines, hunger, and starvation are seldom caused by global, national, or even local shortages of agricultural commodities.

Social Equity and GE Crops

Highlighting the importance of social equity in assessing agricultural sustainability indicates how a systemic, integrated framework could yield a more robust understanding of the potential and the limitations of GE crops to become part of sustainable agriculture. The idea that there are inherent social aspects to technological development, both as “causes” and as “effects” has been well established. Technological diffusion has been associated with changes in social structure, social relations, patterns of work, and access to benefits and costs. A particularly important insight is that technological development and diffusion does not take place in social—or economic or environmental—vacuums. The now classic work of Hayami and Ruttan (1971) demonstrated how agricultural technology options vary by socio-economic contexts. Similarly, the positive and negative impacts associated with any particular technology are rarely uniform across time and space. And what any one group, including farmers, local community residents, and technology developers, may consider a personal or social benefit, another group may consider a personal or social harm.

In the case of GE crops, it is not surprising that most of the extant research and applications have focused on a narrow number of traits for crops such as corn, soybeans, and cotton that are the foundation for the industrial agricultural production system. It is surely not coincidental that one firm that has been most aggressive in developing GM seeds has focused on incorporating a trait that predisposes producers to using other inputs that the firm sells. It is also surely not coincidental that relatively little private sector research has been directed at applying GE to minor crops or to help farming systems adapt to changing or extreme climate conditions, because potential profits from minor or orphan crops are limited.

Although GE crop proponents do not completely ignore broad social impacts, they often address such issues only indirectly and without consideration for long-term consequences. For example, the National Research Council report referenced earlier notes that in the early stages of adoption, the use of GE corn and soybeans, along with the use of glyphosate, was associated with an increase in the use of no-till production systems. Therefore, proponents could point to farmers benefitting from reduced tillage expenses and less soil erosion. They could also list indirect benefits to the public, including improved water quality, due to the usage of a more benign chemical and reduced soil erosion. However, not all farmers are likely to share the benefits of GE crops. Large farms producing a few crops are more likely to benefit from GE crops than small, labor-intensive, and diverse farms because they are developed primarily to reduce input and labor costs within a mass-production system. A technology embedded in an agrifood system that favors a few mass-produced crops reduces the social benefits of agricultural biodiversity. Gene drift from GE crops is also a public harm because it is a type of pollution. Furthermore, the initial benefits to farmers and society of reduced tillage are likely to disappear with the spread of weeds that are glyphosate tolerant, a problem common to widespread adoption of technologies that provide pesticide and herbicide properties.

Similarly, evidence of private economic benefits, such as increased profits for agribusiness firms, is sometimes assumed to be a social benefit. Economic theory tells us that the benefits from farmer adoption of GE crops will be shared among farmers, the supply and marketing firms and the consumer. The proportions of the benefits going to the various parties are subject to determination through the markets and the parties' relative power. However, an explicit use of the concept of social equity challenges us to consider the broader distribution of economic benefits and costs. In the case of GE crops, economic benefits have become concentrated in a few firms that may have gained oligopolistic, or perhaps almost monopolistic, single firm control over crop seed markets. An analysis of change in patent ownership of GE crops between 1988 and 2008 indicates that mergers and joint ventures led to greater levels of concentration. According to an initial data analysis, multiple companies have intellectual property holdings of GE plants: 37 discrete owners of the 525 GE corn patents and 118 discrete owners of the 1013 GE non-corn patents. However, a closer analysis of changing ownership reveals that the top three firms in the GE corn category came to control 85.0% of the patents, and the top three firms in the GE non-corn category came to control 69.6% of patents. These findings indicate that there is substantial concentration of ownership of the intellectual property associated with GE crops (Glenna and Cahoy, 2009). For social equity questions related to GE dissemination to be addressed, research must address how the degree of concentration affects the portfolio of GE and non-GE cultivars available to farmers, as well as how such concentration might be reducing potential economic returns to farmers, which could affect the ability of farmers to pay higher wages to their employees.

Incorporating social dimensions to holistic analyses of GE crop dissemination would lead, for example, to analyses that move beyond the scale of adoption of GE technology in the United States and globally and into the realm of who does and does not adopt the technology, what technological goals farmers have, and whether patterns of adoption mask real or potential conflicts between adopter and nonadopters. A study of Washington state wheat growers revealed that while just over 45% of wheat farmers were highly interested in herbicide-resistant wheat, even more farmers (55%) were highly interested in specialty wheat varieties that could secure premium prices in Asian markets. In addition, a substantial number of farmers (28%), who were predominantly smaller farmers, were highly interested in perennial wheat varieties. Many farmers also expressed concerns about technology agreements they would be required to sign to plant GE wheat (Glenna, Jussaume, and Dawson, in press). These findings point to a diversity of farmer needs and interests often ignored in technology assessments that lack a social equity dimension.

In the case of GE technology, the United Nations Food and Agriculture Organization recently raised concerns that minor crops often produced by small and developing country farmers, are being neglected at the expense of research on major crops. This concern is growing as research shows that university research profiles are increasingly moving in the direction of the private sector by focusing on major crops and major traits (Welsh and Glenna, 2006).

Moving towards Social Equity

New technologies rarely alter foundational social and economic structures. Rather, existing social and economic structures help to explain much of the distribution of environmental, social, and economics risks and benefits from new technologies. In the case of GE crops, the application of the technology in the existing social context has yielded environmental benefits that may or may not continue. The rapid spread of herbicide-resistant weeds can be linked to the broad geographical adoption of GE corn and soybeans that were engineered with a single major trait within the socio-economic context of a mass production framework. The lack of diverse management strategies, including different GE options, which contributed to the rapid emergence of weed resistance, was hardly surprising in the context of U.S. corn and soybean production. Achieving the promise of GE technology for sustainable agriculture is dependent on the adoption of a more flexible and holistic approach to the development, distribution, and use of GE technology, which in turn needs to be based on holistic analysis of technology development. The future economic viability of GE technology, as well as its potential to contribute to positive environmental outcomes, will depend on understanding and addressing the socio-economic structures and variety of farm management methods present in contemporary agriculture.

The proponents of GE technology have been far too sanguine in their predictions about the promise of the technology. Although apocalyptic predictions regarding environmental and economic disasters by some opponents of GE crops have so far not been manifested, we argue that the development and adoption of GE technology has taken place in the context of an agricultural system that is economically and socially inequitable, and this has important implications for the future. Research is needed that focuses on reforming inequitable policies and practices to improve the likelihood that GE applications would contribute to a more sustainable agriculture. As part of such a process, we make the following three suggestions.

First, all relevant stakeholders from multiple levels of the agrifood system, including farmers of different classes and sizes, consumers and citizens, and agribusinesses, should be involved in a collaborative process to ensure that a diverse representation of interests and values guide the GE technology research, development, and application process. One model that might serve as a prototype is participatory plant breeding. Examples already exist of how including farmers in breeding activities and field trials can guide research agendas to become directed at using up-to-date technological approaches for solving problems that farmers face in diverse environments, rather than breeding for mass production in homogenous environments (Mendum and Glenna 2010). Such a process addresses a broader cross-section of farmer interests, promotes agricultural biodiversity, and contributes to addressing challenges that a range of farmers face.

Second, scientific breakthroughs need to be combined with experiential knowledge to overcome the limits of reductionism. As GE crop research has been focused primarily on solving problems associated with a mass-production system, GE crop researchers generally have not been widely viewed as contributing to sustainable agriculture, although there are notable exceptions. A greater focus on social equity may help to break down barriers between GE researchers and sustainable agriculture groups.

Third, GE research needs to shift from a focus on private goods to a focus that includes an emphasis on public goods. This may be achieved with intellectual property and research funding reforms. Novel intellectual property institutions could be altered to promote public researchers' access to proprietary material. Furthermore, it should be recognized that the private sector lacks adequate incentives to focus on public goods research. Public support for public research institutions must be directed at the generation and distribution of minor crops and other non-proprietary agronomic knowledge if GE crops are to generate broader social benefits.

For More Information

Ervin, D.E., Glenna, L.L., and Jussaume Jr., R.A. (2010). Are biotechnology and sustainable agriculture compatible? *Renewable Agriculture and Food Systems*, 25(2), 143-157.

U.S. Government. (1990, November 28). Food Agricultural Conservation and Trade Act of 1990, Pub. L. No. 101-624, 104 Stat. 3359. Washington, DC: U.S. Government.

Glenna, L.L., Jussaume Jr., R.A., and Dawson, J.C. (in press). How Farmers Matter in Shaping Agricultural Technologies: Social and Structural Characteristics of Wheat Growers and Wheat Varieties. *Agriculture and Human Values*.

Glenna, L.L. and Cahoy, D. R. (2009) Agribusiness Concentration, Intellectual Property, and the Prospects for Rural Economic Benefits from the Emerging Biofuel Economy. *Southern Rural Sociology*, 24(2), 111-129.

Glenna, L.L., and Jussaume Jr., R.A. (2007). Organic and Conventional Farmers' Opinions on GM Crops and Marketing Strategies. *Renewable Agriculture and Food Systems* 22(2): 118-124.

Glenna, L. (1999). Systemic Constraints to Ecological Well-being: The Case of the 1985 Food Security Act. *Rural Sociology*, 64(1), 131-155.

Hayami, Y. and Ruttan, V. (1971). *Agricultural Development: An International Perspective*. Baltimore, Md: Johns Hopkins Press.

Lacy, W.B., Glenna, L., Biscotti, D. and Welsh, R. (2009). Agricultural Biotechnology, Socioeconomic Effects, and the Fourth Criterion. Pp. 1-16 in Flickinger, M.C. (Ed.) *Wiley Encyclopedia of Industrial Biotechnology: Bioprocess, Bioseparation, and Cell Technology*. Hoboken, N.J.: John Wiley & Sons, Inc.

Mendum, R. and Glenna, L.L. (2010). Socioeconomic Obstacles to Establishing a Participatory Plant Breeding Program for Organic Growers in the United States. *Sustainability*, 2, 73-91.

National Research Council. (2010). Impact of Genetically Engineered Crops on Farm Sustainability in the United States *Washington, D.C.: National Academies Press.*

Waldman, A. (2002, December 2). India's Poor Starve as Wheat Rots. *New York Times*. Available online: http://www.nytimes.com/2002/12/02/world/poor-in-india-starve-as-surplus-wheat-rots.html

Welsh, R. and Glenna, L. (2006). Considering the Role of the University in Conducting Research on Agri-biotechnologies. *Social Studies of Science*, 36(6), 929-942.

World Bank. (2005). *World Development Report 2006: Equity and Development* New York, New York: Oxford University Press.

Leland L. Glenna (LLG13@psu.edu) is Assistant Professor of Rural Sociology, Department of Agricultural Economics and Rural Sociology, Pennsylvania State University, University Park, Pennsylvania. Raymond A. Jussaume (rajussaume@wsu.edu) is Professor, Department of Natural Resource Sciences, Washington State University, Pullman, Washington.

CHOICES a publication of AAEA Agricultural & Applied Economics Association

www.ChoicesMagazine.org

2nd Quarter 2010, 25(2)

Can Genetically Engineered and Organic Crops Coexist?

Catherine Greene and Katherine Smith
JEL classification: Q01; Q13; Q57

Over the last decade, American consumers fueled a fast-growing market for organic food and U.S. farmers flocked to genetically engineered (GE) varieties of several major U.S. crops. The potential for GE crop production to impose costs on organic production, via accidental pollination and other mechanisms, underscores the problem of coexistence between GE and organic crops. Here we review evidence that consumer demand has led to markets for products differentiated on some basis of GE status, and that maintaining the integrity of those differentiated product markets relies on interventions such as physical distancing or product segregation. Further, at present, the costs required to support the coexistence of all markets is borne disproportionately by producers and consumers of organic food in the United States.

Consumer Demand for Organic and Non GE Food

Demand for organic food and other products in the United States has steadily increased since the late 1990s, providing market incentives for U.S. farmers across a broad range of products to grow organic. Although the market in the United States is relatively small, it is quite strong and has realized double-digit annual growth rates over the last decade. In 2010, sales of organic food continue growing much faster than in the overall food market. Congress passed the Organic Foods Production Act of 1990 to establish national standards for organically produced commodities, and USDA's subsequent national organic program (http://www.ams.usda.gov/nop/) regulations and certified organic label played important roles in providing consumer assurance, most likely contributing to the growth in the U.S. organic market. U.S. sales of organic products were $23 billion in 2009—about 3.5% of total at-home food sales—and will reach $25 billion in 2010, according to the *Nutrition Business Journal*.

USDA's national organic standards are process-based. They address the methods, practices, and substances used in producing and handling crops, livestock, and processed agricultural products that can be certified as organic. These requirements apply to the way the product is created, not to measurable properties of the product itself. USDA regulations specify that organically produced food cannot be produced using genetically engineered materials. While these regulations are process-based and do not set a threshold limit for the accidental presence of GE materials in organic products, organic buyers in the United States and elsewhere have set thresholds and are increasingly requiring testing and other compliance measures. During the USDA's final rule-making process, organic consumers unequivocally stated their preference that genetic engineering technologies be excluded from organic production and processing. This was recently reconfirmed in the context of animal cloning.

Although not regulated by the Federal government, there is evidence that firms in the United States can capitalize on consumer preferences by labeling food as having been grown without the use of genetic engineering. For example, WhiteWave Foods (www.whitewave.com/) sells Silk brand organic soymilk, which meets all USDA organic production and processing standards, including the prohibition on the use of genetic engineering, as well as Silk soymilk that is produced from non-genetically modified crops. WhiteWave has its own testing protocols to ensure that genetically modified crops are not present in these products: soybean seeds are tested and only approved seeds are planted; samples are pulled and tested as beans are harvested before entering a storage silo; and composite samples are taken and tested as sacks are prepared for delivery. The product commands a premium price to cover the costs of such a program—and consumers are paying it. According to industry estimates, packaged food containing a non-genetically modified organism (GMO) label claim accounted for nearly $787 million in sales in the United States between April 2009 and April 2010.

In the United States, the private sector has taken the lead in setting product-based standards to minimize the risk of contamination of non-GE products. Individual companies have used a patchwork of non-GMO standards and label claims over the past decade. Spurred by organic and natural food companies needing a consistent, verifiable and reliable standard, a nonprofit group, the Non-GMO Project, emerged recently with an independent verification system for products made according to best practices for GMO avoidance, including testing of risky ingredients—for example, soybeans. The “Non-GMO Project Verified” label claim is based on non-GE product traceability, segregation, action thresholds and other practices for GMO avoidance. Action thresholds are set for high-risk inputs and products, such as corn and soybeans, and are set at 0.9% for food grains, for example. The Non-GMO Project avoids legally and scientifically indefensible claims that products are 100% GE-free. A broad set of U.S. organic and natural food companies have already joined the non-GMO Project to use its non-GE testing and labeling protocol—including Eden, Hodgson Mill, Lundberg’s Family Farms, Nature’s Path Organic, Organic Valley, Rice Select, Snyder’s of Hanover, Straus Family Creamery, and many others. Whole Foods Market, the largest natural foods supermarket chain in the United States, is also partnering with the Non-GMO Project to use their non-GE testing and labeling protocol for its private label products.

Many important foreign markets have regulatory requirements for non-GE products, and buyers may also set more stringent private standards in these countries. The European Union, (EU) for example, has mandatory GE labeling and coexistence policies. All products marketed in the EU for which the content of a product exceeds 0.9% GE ingredients must be so labeled. This policy places a labeling cost on GE crop producers. Yet, results from public polls in the United States and elsewhere show “overwhelming support for labeling of genetically modified food” (Onyango, Nayga, and Govindasamy, 2006). Consumer preference for non-genetically engineered food is not as well documented.

There is ample opportunity for U.S. crop producers to take advantage of the many production benefits that GE crops provide. The vast majority of U.S. soybean, cotton and corn producers plant genetically engineered varieties, attesting to GE crops’ commercial production appeal. Although recent industry surveys indicate that a majority of U.S. consumers buy organic products at least occasionally, food purchase data suggest that a majority of U.S. consumers are either unaware of or indifferent to the presence of GE ingredients, or are unable to afford the prices that organic and non-GE foods command.

Why Can’t We All Just Get Along?

Clearly we have a largely GE-indifferent mainstream food market, a well established and growing market for foods differentiated by the organic label, and evidence in the United States and abroad of another market for products specifically differentiated by their lack of GE ingredients. The coexistence of these markets is threatened by the possibilities of transgene flow, GE-induced resistance of pests to pest control products, product comingling, and other externalities. We note that this is the case not just for organic markets and GE crop production, but also for commodities differentiated in other ways. For example, in the United Kingdom, two differentiated varieties of non-GE rapeseed are produced for oil–one for edible oil, the other for an industrial grade product that is prohibited for human consumption. The different markets rely on strategies that assure coexistence without interference with one another.

Contamination of differentiated products can occur at many different stages in the production and processing chain. Gene flow from genetically-altered crops, even those approved for food uses, is a particular issue for farmers that target organic food markets, but other modes of contamination may also occur. For example, in 2002 transgenic corn plants engineered to express a vaccine were found to have “volunteered” in an otherwise normal corn planting. This discovery led to incineration of plants, both corn and soybean, across a wide acreage and fines on the firm that produced the transgenic variety. In 2000, StarLink, a gene-altered corn approved only as animal feed, was found in corn chips and other food products throughout the United States, prompting product recalls. StarLink corn was commingled with other corn after it was harvested.

Failure to manage biological confinement can lead to disruption of domestic and international markets for organic products since international and USDA organic regulations prohibit the use of genetically modified organisms in organic crop production. Markets for organic food differ in their tolerance levels for the adventitious presence of genetically modified organisms, with some countries and buyers setting a zero tolerance, and others allowing small amounts, generally under 1%. The tolerance level that organic farmers must meet has largely been market driven, rather than regulatory driven in the United States.

It is no surprise that organic farmers perceive contamination as a big issue. The University of Maryland in cooperation with a research team from USDA's Economic Research Service conducted a set of focus groups across the United States to explore the risks faced by organic farmers, how they are managed, and needs for risk management assistance. Participants in these sessions included operators of about 60 farms, producing many different organic crops in various parts of the country. Contamination of organic production from genetically engineered crops was seen as a major risk, particularly by grain, soybean, and cotton farmers. Organic farmers at all the focus group sessions expressed considerable concern about risks from the use of genetically engineered crops by conventional farmers. Contamination from pollen drift from genetically engineered crops was seen as a particularly serious risk, one that the participants felt is now resulting in lost organic sales.

Organic farmers also pointed out that genetically engineered varieties may destroy the effectiveness of natural pest controls. For example, many organic farmers use Bt-based foliar pesticides, which are approved for organic use, to control insects. In recent years, transgenic varieties of corn containing the Bt protein have been developed, and organic farmers worry that their widespread use will hasten development of Bt resistance by insects and limit the usefulness of Bt organic pesticides.

Many of the organic farmers expressed a broad complaint about responsibility for transgenic crop varieties. They explained that companies developing genetically engineered crop varieties provide a technology that is useless to organic farmers, while at the same time exposing organic producers to substantial risks.

Successful Coexistence Requires Management Strategies at Many Levels

The coexistence of organic and GE crops relies on management practices, segregation and identity preservation measures at every step in the food chain, from seed production through food or feed processing and transportation.

Organic farmers use numerous management strategies—buffer zones, careful timing for crop planting, crop monitoring—to minimize to possibility of accidental contamination. One way of managing the risk of transgenic contamination is to plant the organic crop one to two weeks later than nearby conventional farmers plant so that the organic crops would not pollinate at the same time as the predominant genetically engineered varieties. This strategy has only been modestly successful because cool and wet spring weather can delay plant growth such that corn plants pollinate at about the same time regardless of planting date. Some U.S. producers and processors have grown organic corn for seed in countries with less widespread adoption of GE crops in order to have a two-mile buffer zone. In addition to adding or increasing the size of buffers, adjusting the timing of crop planting, and changing crop location, additional risk management strategies that organic farmers may use to mitigate the risk of transgenic contamination include altering cropping patterns or crops produced and discontinuing the use of inputs at risk for contamination. The use of any of these risk management strategies may increase the costs of producing organic and non-GE crops.

Growers of GE crops that have pesticidal properties, such as Bt corn and cotton, also take steps to maintain susceptibility of the pest population. They are required to set aside refuge areas—areas planted to conventional varieties of the same crop—so that the pest population includes genes of pests that are not likely to become resistant. The strategy's success relies on the cooperation of GE variety producers and EPA enforcement of the practice. Set-asides are not costless but GE producers, as well as non-GE producers, benefit from their success.

Post-harvest preservation of the organic or non-GE trait is accomplished by segregating the organic crops and their downstream products from GE crops. Segregation is exceptionally costly. Segregating organic from GE crops requires substantially larger investment in infrastructure for handling the crop commodity and the intermediate and final products. Harvesting equipment, sorting processes, on-farm or elevator storage facilities, containers and other transportation vessels, storage at point of shipment, and processing facilities essentially have to be distinct for organic and for GE. In some cases, facilities used to process GE crops may also be used for organic crops by cleaning the facility first. For example, a cotton gin is cleaned by putting an initial load of organic cotton through the gin and treating that load as conventional product and forgoing the organic price premium on it.

A major organic producer organization in the United States, the Organic Farmers Agency for Relationship Marketing (OFARM), recently adopted its own protocol for minimizing GMO contamination. Member groups, including the top organic grain marketing cooperatives in the Midwest, have agreed to the detailed set of GMO avoidance practices, including product testing for seeds and feeds, and a sampling protocol for products.

Despite producer efforts to avoid GE contamination, one of the top organic and non-GE grain wholesalers in the United States reports that it's rejecting an increasing percentage of the arriving loads because they test higher than 0.9% for genetically engineered material. When a load is rejected, a producer loses their organic or non-GE price premium for the product, incurs additional trucking costs for transportation to a buyer who purchases GE grain, and may have other losses. According to Lynn Clarkson, of Clarkson Grain, several factors explain their recent rise in rejected loads. First, the Non-GMO Project has sensitized many food processors regarding GMOs, and the numerous food processors that have joined this project are now demanding Non-GMO Project Verified ingredients. Also, more organic buyers are contracting for grain with non-GMO verification as well as organic certification. Clarkson Grain is conducting more GMO testing to comply with their clients' wishes. In addition, a major tool for identifying GE contamination—the visual distinction of yellow GE corn kernels and white non-GE kernels—was lost several years ago when major non-GE white corn buyers also starting purchasing white corn from producers using GE crops.

*Figure 1. OFARM Policies and Protocol for Minimizing GMO contamination**

OFARM Policies and Protocol for Minimizing GMO contamination*

On-farm practices:

- Use third-party tested seeds and feeds of concern to ensure purity
- Keep records of test results on feed and input sources
- Keep tested seeds separate from GE seeds
- Use appropriate field buffers based on specific crop distances
- Clean and visually inspect planter and drill boxes before use
- Use physical separation or minimum-foot border rows
- Report actual non-GE acres planted for OFARM contracts to certifier
- Be aware of neighbor's crops and planting dates
- Use alternative planting dates for corn and canola
- Maintain planting history for non-GE contract fields
- Clean combines, grain drills, planters, and other equipment
- Visually verify that custom or shared combines are free of other grain
- Use a flush run to assure equipment is free of contaminants
- Use identity-preserved stickers or other methods to label non-GE bins
- Clearly instruct drivers about the identity preserved nature of shipments

Product loading and shipment practices:

Producer responsibilities:

- Ensure proper documentation for identity-preserved grain
- Take and maintain representative sample(s) as grain is loaded into storage
- Clearly instruct drivers about the identity preserved nature of shipments
- Inspect truck for cleanliness

Driver responsibilities:

- Clean and inspect all equipment used for loading and transporting grain
- Clean and wash trucks according to protocol
- Complete a truck inspection affidavit as the truck is loaded

OFARM coordinates marketing for member groups:
Buckwheat Growers Association of Minnesota
Kansas Organic Producers Association
Midwest Organic Farmers Co-op
Montana Organic Producers Co-op
NFOrganics
Organic Bean and Grain
Wisconsin Organic Marketing Alliance

Coexistence Problems Affect Producers' and Consumers' Welfare

Moschini, Bulut, and Cembalo (2005) have demonstrated that the segregation and identity preservation costs imposed on the organic sector by the introduction of a GE innovation can be so high that they overwhelm the welfare gains, or economic benefits, from the GE innovation itself. This finding relies on the existence of a non-GE differentiated market, like organic, at the time of the GE introduction.

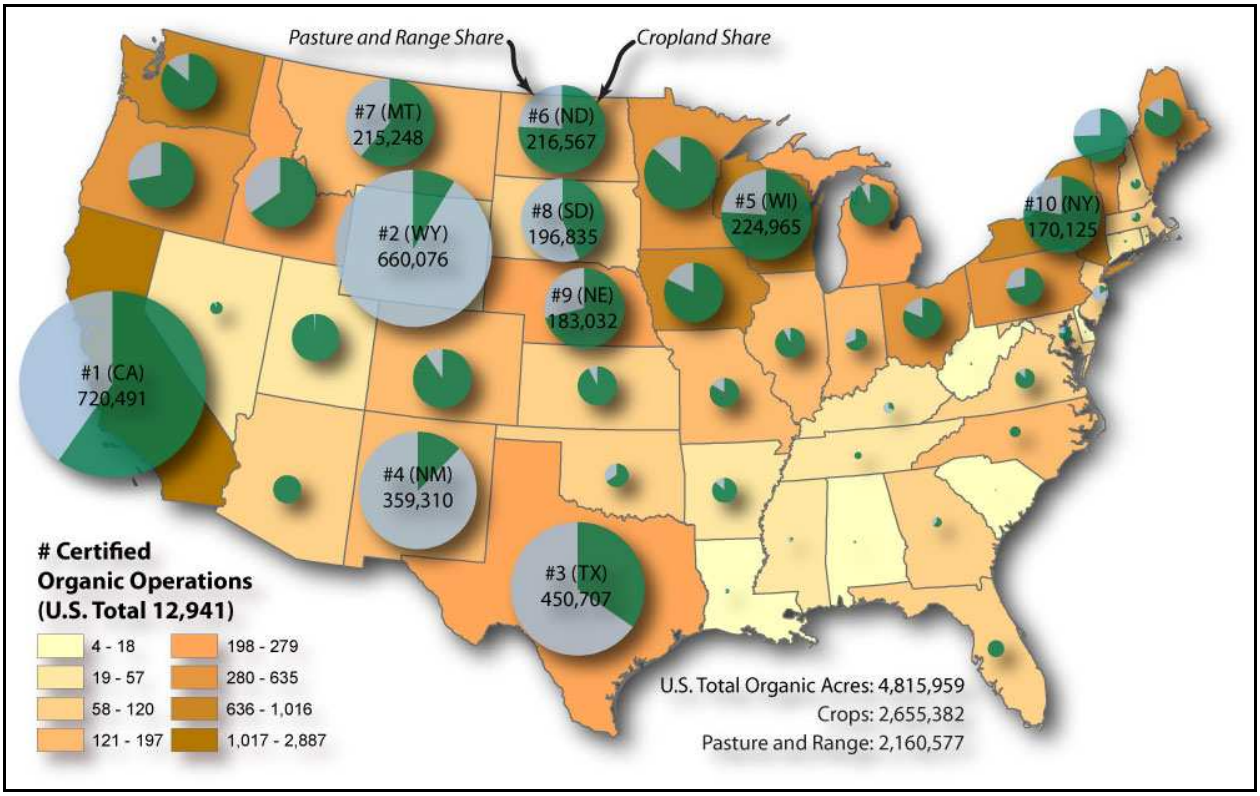


Figure 2. Organic Operations Accounted For Less Than 1% of Total Crop Acreage in 2008

We hypothesize for field crop producers in the United States that the widespread use of genetically modified crops may also play a significant role in dampening the adoption of organic farming systems. U.S. producers dedicated approximately 4.8 million acres of farmland—2.7 million acres of cropland and 2.1 million acres of rangeland and pasture—to organic production systems in 2008. California remains the leading State in certified organic cropland, with over 430,000 acres, over 40% of which is used for fruit and vegetable production. Other top states for certified organic cropland include Wisconsin, North Dakota, Minnesota, and Montana. However, for the crops for which adoption of GE technology is greatest, organic production is low. Only a small percentage of the top U.S. field crops—corn (0.2%), soybeans (0.2%), and wheat (0.7%)—

were grown under certified organic farming systems, compared with vegetables (7%) and fruits (3%). U.S. organic soybean acreage has remained relatively flat since the early 2000s despite increasing demand for organic feed grains and consumer products such as soymilk, and U.S. feed grain distributors and soy product manufacturers report sourcing organic soybeans from other countries. Meeting government and private standards for non-GE crops is easier for farmers in many countries outside the United States where adoption of GE crops is low.

Who Pays for Coexistence?

Depending upon the regulatory or technological fix employed, and/or liability assignment, organic producers and consumers and/or GE seed developers and users can end up paying to assure coexistence. In the EU, mandatory labels for GE products shift some of the cost of coexistence to GE product processors and sellers. The European Commission published guidelines for developing national strategies and practices to ensure a fair balance between the interests of GE and non-GE farmers in July 2003, and recently determined that Member States had made significant progress in developing national strategies for coexistence. The coexistence approach in a number of these countries is to require GE producers to use buffers and other prevention strategies and to make them liable for economic damages to non-GE producers. Another coexistence strategy that is being examined in Europe is the use of insurance markets to help compensate for the economic losses experienced by organic and other non-GE producers (Koch).

In the United States, an alternative approach has been used, implicitly allocating risks and costs to non-GE producers. Organic and other non-GE products are labeled, and the non-GE producers assume the full costs and liability of accidental contamination from GE crops. By 2002, 8% of respondents to a national organic producer survey reported having direct costs or damages, such as testing costs and loss of organic sales or markets, related to GE crop production. The open-ended economic risk to non-GE producers from accidental contamination by GE crops may dampen prospects for growth in the domestic organic farm sector, particularly as GE technology spreads to the food crops that dominate the organic sector.

Moving toward a more level playing field for organic and non-GE producers in the United States could involve a mix of strategies. For example, U.S. organic and non-GE producers might continue to incur some of the extra costs associated with GE production, such as the costs of GE testing, but have access to compensation if their crop loses organic or non-GE status, and attendant price premiums, due to GE contamination. Or, the private sector could step in by, for example, stacking a trait for unusual seed color or shape to avoid comingling. A public/private partnership may enhance coexistence and make organic, non-GE and GE production more sustainable in the United States.

For More Information

Hanson, J., Dismukes, R., Chambers, W., Greene, C. and Kremen, A. (2004). Risk and risk management in organic agriculture: Views of organic farmers. *Renewable Agriculture and Food Systems*: 19 (4), p. 218-227.

Koch, B. A. (2007). Liability and Compensation Schemes for Damage Resulting from the Presence of Genetically Modified Organisms in Non-GM Crops. European Centre of Tort and Insurance Law, Contract 30-CE-0063869/00-28.

Moschini, G., Bulut, H. and Cembalo, L. (2005) On the Segregation of Genetically Modified, Conventional and Organic Products in European Agriculture: A Multi-market Equilibrium Analysis. *Journal of Agricultural Economics*, 56 (3) pp 347–372.

Moschini, G. (2008). Biotechnology and the Development of FoodM: Retrospect and Prospects. *European Review of Agricultural Economics:* 35 (3) pp. 331-355.

Murphy, D. (2007). *Plant Breeding and Biotechnology: Social Context and the Future of Agriculture*. Cambridge, UK: Cambridge University Press.

Non-GMO project. (2010). Non-GMO project working standard, version 6, June 7, 40 p. Available online: http://www.nongmoproject.org/.

Onyango, B., Nayga, R.M., Jr., and Govindasamy, R. (2006). U.S. Consumers' Willingness to Pay for Food Labeled 'Genetically Modified', *Agricultural and Resource Economics Review*, 35 (2) pp. 299-310.

Catherine Greene (cgreene@ers.usda.gov) is a Senior Economist with the U.S. Department of Agriculture's Economic Research Service. Katherine Smith (ksmith@ers.usda.gov) is the Administrator of USDA's Economic Research Service.

The views expressed in this article are the views of the authors and not necessarily the views of the United States Department of Agriculture.

CHOICES
a publication of AAEA Agricultural & Applied Economics Association
www.ChoicesMagazine.org
2nd Quarter 2010, 25(2)

What Drives Academic Bioscientists: Money or Values?

Sharmistha Nag, Hui Yang, Steven Buccola, and David Ervin
JEL Classifications: O31–O34, O38

No examination of the role of GE crops in the sustainability of U.S. agriculture is complete without understanding what drives academic bioscience. The National Research Council's 2010 report on the role of genetically engineered (GE) crops in U.S. farm sustainability underscores not only their successes, but the challenges they now introduce. The challenges include protecting against herbicide resistance, tracking and controlling water pollution, measuring and guarding against gene flow to non-GE varieties, and attending to such potentially public-good issues as climate change mitigation, minor-crop development, and nitrogen fixation. In the shorter term, successes in these areas will depend on commercial trait development and on the farm management practices linked to it. In the longer term, however, it will depend on the drivers influencing academic bioscience, where most fundamental research underlying genetic modification—and much of the translational work bridging the gap between proof-of-concept and product development—begins.

Such drivers increasingly can be understood in supply-and-demand terms because universities increasingly view themselves as suppliers of research deliverables and demanders of research money. On the other side of these two markets, journals, governments, and firms seek research deliverables and public agencies and firms supply research monies. Yet part of the reason most professors work at universities is to pursue noncommercial interests. Predicting academic research directions thus requires we consider professors and administrators as seekers of both monetary resources and professional satisfaction.

Bioscientists' Motives

To capture the personal and commercial aspects of university bioresearch, we consider four of its dimensions: (a) the bioscience discipline—reflected in the scale of the research object, from sub-cellular to entire ecosystem; (b) the position of the research on the basic-to-applied continuum; (c) the potential for patentability or other types of excludability—of the finding; and (d) the interest group served. It is important to ask how the scientist's human and institutional capital, program funding, academic culture, and market environment affect these characteristics and contribute to human welfare.

Funding agencies' research budgets can offer some answers. But the variety of scientific activity hidden in those gross statistics rarely distinguishes among the many issues that research policy makers need to understand. For example, aggregate data don't allow distinguishing between a scientist's willingness to engage in, and an agent's willingness to fund, a particular line of research. Such distinctions are best drawn by examining the individual scientist's behavior.

Social scientists have theorized about, and tested for, what motivates scientists to do what they do. Early analysts argued that institutional influences, such as university structures and cultures, played dominant roles, leaving little discretion to the individual scientist. More recently, scholars have thought of individual scientists as having their own motives and abilities and facing their own constraints in research program development. We draw on both the institution-based and individual-based theories here to examine how academic scientists make decisions about the types of research questions they ask.

Our data for doing so come from a 2003 – 2004 national survey of academic bioscientists who conducted research on molecular or cellular structures with implications for agriculture, forestry, or aquaculture. The scientists identified by their department chairs as conducting such research were drawn from a random sample of 20 Land-Grant, 25 public non-Land-Grant, and 25 private universities. Each researcher was sent an on-line questionnaire asking about their annual budgets by funding source, types of laboratory assistants, grant-based inputs such as equipment and cell lines, university resources, the respondent's bioscience discipline and current main study topic, the basicness and potential excludability of their approach to that topic, academic rank, and intensities of view on a range of professional scientific norms. Sixty-four percent of the 1441 scientists we contacted responded, giving a total sample of 922.

We asked each respondent to indicate the percent of his research portfolio that was basic—adding to fundamental knowledge—and the proportion that was applied—creating a new product or a solution to a problem. We also asked him to estimate the proportion of his research he expected to be nonexcludable in the sense of not being property-right protectable —and hence *not* restrictable to paying parties. The meanings of basic and applied, and nonexcludable and excludable, may vary somewhat across bioscience disciplines. In order to reduce the potential for conflicting interpretations, we provided definitions and examples of these four research characteristics. That respondents showed little evidence of inconsistency is suggested by the fact that when asked to indicate their projects' basicness and excludability on a 6-point Likert-scale, such as "how basic was your research?", their responses were highly correlated with their percent-of-program responses.

Sixty-seven percent of the mean respondent's research portfolio was basic and 33% applied. Eighty-five percent was reported to be nonexcludable and the remaining 15%

excludable. The average current annual laboratory budget was $229,000 from federal and state public sources, 18% of that from the National Science Foundation (NSF), 33% from the National Institutes of Health (NIH), 18% from the U.S. Department of Agriculture (USDA), and 17% from state governments. Nearly $51,000 was derived annually from private sources, 53% of it from industry firms and trade associations and 47% from foundations. Forty-seven percent of the scientists were from Land Grant universities, 35% from public non-Land-Grant universities—such as the University of Texas—and 18% from private universities such as Stanford. Medical school faculty were strongly represented, suggesting a significant overlap between human-health and agricultural biotechnology.

Research Basicness and Excludability

The right mix of basic and applied, and of excludable and nonexcludable, discoveries for addressing GE crop challenges depends on the problem context. We can begin that inquiry however by asking about the *factors* affecting these research program features. Funders use their requests-for-proposals to influence the type of research they seek, for example a study on crop biofuels. On the other hand, every funder serves a variety of interest groups and supports research in a variety of areas. And academics have their own preferences among potential funders. So it is useful to ask how another dollar from a particular money source influences a researcher's objectives. To do that, we must control for factors other than the money the scientist receives. We also must account for his human capital—represented for example by his academic rank, his university culture, and the professional norms that partly guide his research life and choices.

When we do so, we find that the proportions of a bioscientist's program that are basic and nonexcludable are strongly influenced by her professional norms regarding the value of theoretical research, scientific curiosity, patenting, and nonexcludable—public—benefits. Our scale for measuring these norms runs from 1 to 7, increasing numbers reflecting more intense agreement with the norm. The more she says she is constitutionally oriented toward achieving theoretical breakthroughs or indulging her scientific curiosity, the more she engages in basic research. The more she is oriented toward patenting, the more excludable her research turns out to be. The statistical significances of these normative factors were greater than for any of the other factors, such as type of funding source, we considered.

Table 1. Factors Affecting Bioscience Research Basicness and Nonexcludability[a]

Factors	Basicness and Nonexcludability	
	Percent Basic	***Percent Nonexcludable***
Research Program Characteristics		
Percent Basic		0.16
Percent Nonexcludable	0.27	
Research Funding		
Public Funding ($1,000)	0.03	-0.01
Private Funding ($1,000)	-0.16	0.03
Scientist's Norms		
Contribute to Theory (1 – 7 scale)	6.60	
Scientific Curiosity (1 – 7 scale)	4.12	
Chance to Patent (1 – 7 scale)		-5.72
Create Nonexcludable Benefits (1 – 5 scale)		1.65

[a]*Numbers are changes in the percent of the scientist's research portfolio that is basic or nonexcludable caused by a one-unit change (shown in parentheses) in the indicated factor.*

The influence of each factor is shown in Table 1. As one would expect, more nonexcludable research programs tend to be more basic, and more basic programs more nonexcludable. But those relationships aren't very strong. Boosting the basic portion of a scientist's portfolio one percentage point boosts the nonexcludable portion by only 0.16 points. This is a potential impact of the Bayh-Dole Act and related court rulings, which have expanded the range of basic scientific innovations that can be patented. The Bayh Dole Act allowed recipients of federal research funding intellectual property control of the inventions and other intellectual property that resulted from such funding.

Neither the source nor amount of the scientist's funding has a statistically significant impact on the proportion of her work she regards as excludable. Public money, in other words, is just as likely to encourage patentable or otherwise market-protectable research as is private money, another likely Bayh-Dole influence. Funding source does, however, affect research basicness. While a $1000 rise in the publicly funded portion of the scientist's portfolio boosts the *basic* content of her research program by only 0.03 percentage points, a $1000 rise in the privately funded portion boosts its *applied* content by 0.16 percentage points. Speeding up GE crop innovations by shifting to more downstream research can be accomplished by allocating more funding to the private sector. This, however, will be effective only if foundational science doesn't suffer too greatly as a result.

Research Basicness and Object Size

The research topics in bioscientists' laboratories also can be characterized through the sizes of the objects they examine. Because GE crops, such as in Bt cotton, are often produced through manipulation of sub-cellular material, the innovation rates depend directly on the magnitude of laboratory effort at the sub-cellular and cellular levels. Yet the implications of these discoveries, such as the non-target-insect mortality associated with Bt technology or the watershed effects of shifting to more herbicide resistant crops, are understood only at the organism and ecosystem levels. Research at those larger scales therefore provides useful information for future sub-cellular innovation. As it turns out, a research project's object size is only moderately correlated with its basicness. Thus, accounting separately for these two bioscience program features is important for understanding the rate, character, and control of genetically engineered innovations in agriculture.

We asked four academic bioscientists who did not participate in our survey to examine each of our 922 respondents' research topic descriptions and classify each by object size. Thirty-five percent of the topics focused on sub-cellular particles, 11% on cells, 9% on organs, 25% on organisms, 12% on natural ecosystems, and 8% on managed ecosystems. Respondents who said they were biochemists or cell or molecular biologists—60% of our sample—conducted work mostly at the sub-cell or, to a lesser extent, cell or organism level. Pathologists—10% of the sample—were predominantly in organism research, and geneticists—20% of the sample—in sub-cellular or organism research. For simplicity, we here combine sub-cell and cell topics into a "cellular" group, organ and organism into an "organism" group, and natural and managed ecosystems into an "ecosystem" group.

Basicness was measured by asking the scientist to indicate on a six-point scale the degree of basicness of the typical project in his current research portfolio, in contrast to the proportion of her research program used above. We called "basic" any topic with a response in the 1-to-3 range, and "applied" any topic in the 4-to-6 range. Finally, we categorized each topic according to the combination of basicness and object-size it fell into: basic cellular, applied cellular, basic organism, applied organism, basic ecosystem, or applied ecosystem. We used statistical methods to determine how the scientist's human capital and institutional culture, professional norms, and funding sources affected the likelihood she would conduct research that fell into each of these six categories. To our knowledge, this is the first investigation of such relationships.

Influences on Basicness and Object Size

Table 2. Funding-Source Impacts on Research Basicness and Object Size[a]

Funding Source and Type	**Object Size**		
	Cell Level	**Organism Level**	**Ecosystem Level**
USDA			
Basic	-0.14	-0.08	-0.02
Applied	0.22	0.21	0.08
Industry			
Basic	-0.95	-0.14	-0.05
Applied	0.17	0.39	0.12

[a]Numbers are the changes in the percent of research at the indicated basicness and object size caused by boosting funding from the indicated source by one percentage point, and reducing NSF funding by the same amount. Impacts of NIH and state funding are not shown.

Table 3. Professional-Norm Impacts on Research Basicness and Object Size[a]

Professional Norm	**Object Size**		
	Cell Level	**Organism Level**	**Ecosystem Level**
Theory Norm			
Basic	5.35	2.19	1.12
Applied	0.29	-2.63	-1.72
Patenting Norm			
Basic	-2.70	-0.95	-0.73
Applied	2.61	2.81	-1.45

[a]Numbers are the changes in the percent of research at the indicated basicness and object size caused by a one-point rise in the importance of the indicated professional norm. Impacts of NIH and state funding are not shown.

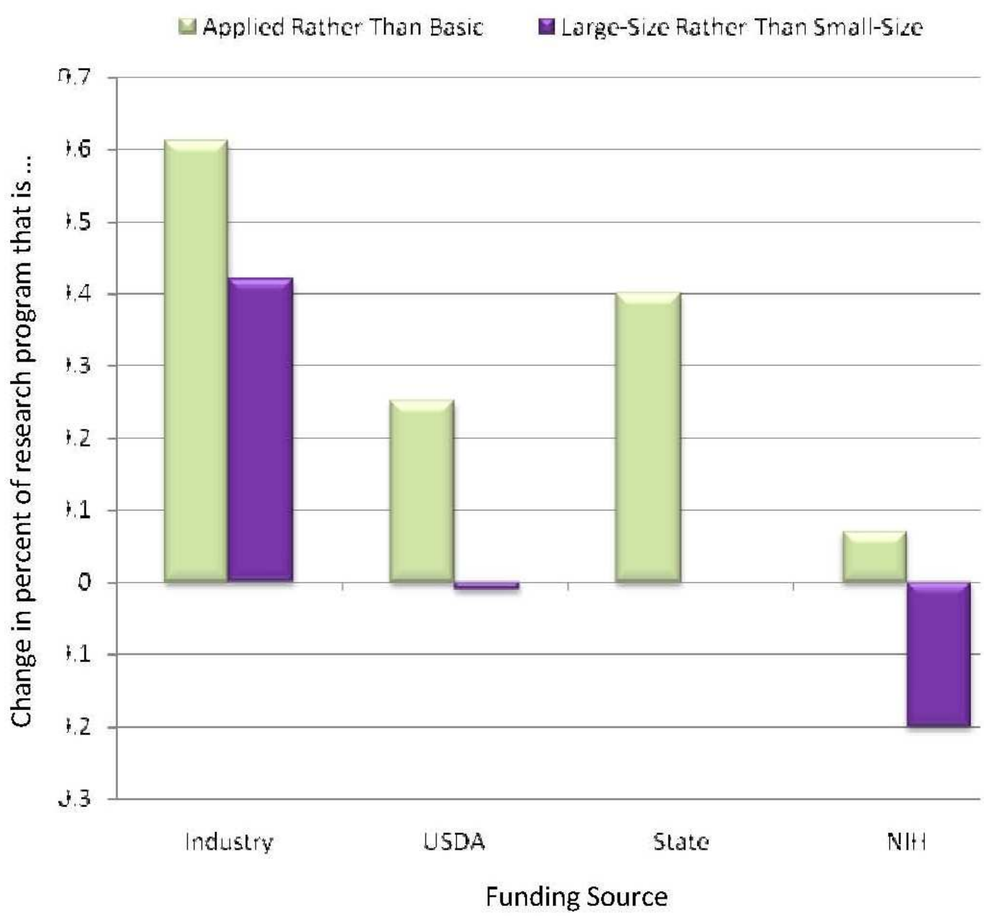
The scientist's rank and university type had, by themselves, little influence on these research choices. But the sources and amounts of her funding, and her professional norms, were important. USDA and industry funding effects are given in Table 2, while patenting-norm and theory-norm impacts are presented in Table 3. The USDA and industry sections of Table 2 show the research-choice effects of boosting USDA or industry funding by one percentage point while reducing NSF funding the same amount. Because NSF is the most basic-research-oriented of the major funders, this reveals the net effect of shifting funding from the most basically inclined to the more application-oriented agencies. For example, boosting USDA funding one percentage point brings a 0.22 percentage-point rise in applied cellular research. Table 3 shows the research-topic impacts of a one-point rise in the scientist's normative orientation toward, respectively, theoretical contributions and patenting. We selected these norms not as a dichotomy but as two topical scientific issues of high relevance to bioscience.

Our findings suggest that routing more GE-crop and other biotechnology funding through biotech firms or the U.S. Department of Agriculture pushes academic bioscientists away from basic and toward applied research at the cell, organism, and ecosystem levels. For example, the -0.95 value in the industry-funding part of the left side of table 2 says shifting one percentage point of the scientist's funding from NSF to biotechnology firms reduces by 0.95 percentage points the likelihood he will conduct basic sub-cell or cellular research. And it will raise by 0.17 points the likelihood he will conduct applied sub-cell or cellular research. However, the larger the research study’s object size, the less does industry funding push it in the applied direction. USDA support creates a similar but more modest inducement toward applied topics. And as with biotech firms, the inducement is lower on the ecosystem than on the cellular side of the object-size continuum.

Table 2 also can be read horizontally to show how industry and USDA funding affect research object size. Shifting one percentage point of the scientist's support from NSF to industry reduces the prospect of basic organism-level research by only 0.14 percentage points but, as noted above, the basic cell-level research by 0.95 points. Thus industry sponsorship leads, comparatively speaking, strongly away from basic sub-cellular and cellular work. And among applied programs, industry leads particularly toward research at the organ and organism levels. USDA sponsorship has the same general effect, albeit at slightly lower magnitudes.

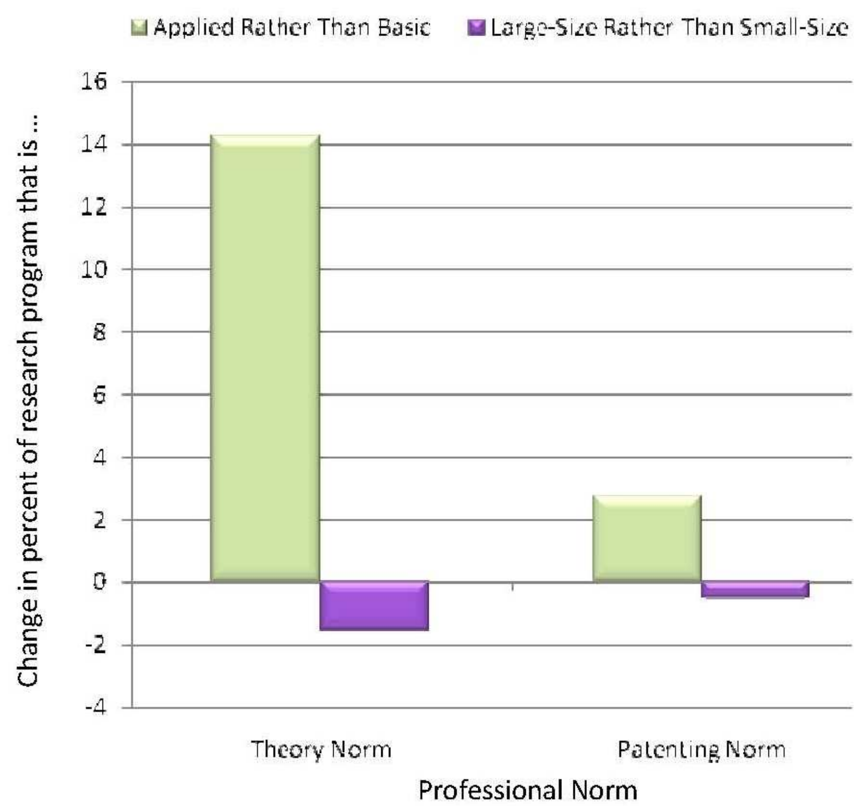
Table 3 shows professional norms exert strong influences on research-topic choice. Examples of their influences: a one point rise in the scientist's theory norm induces a 5.35 percentage point rise in the chance the scientist will be found to conduct basic cellular research, and a 1.12 point rise in the chance she will be found to conduct basic ecosystem studies. A one point rise in the scientist's orientation toward patenting reduces by 2.70 percentage points the likelihood of her conducting basic cellular research and boosts by 2.61 points the likelihood of applied cellular work, resulting in a net 5.35 percentage point net rise in the likelihood she will conduct applied research if she is sub-cellular or cellular scientist. Expressed in proportionate terms, the professional norms examined in this study had on average four times as much research influence as funding sources did.

Among organism scientists, rising patenting orientations create a similar but smaller impulse toward applied topics. At the same time, they induce modest shifts from larger to smaller-scale research, where more opportunities for patenting are found. Scientists oriented more toward theory are more likely to conduct basic research. Interestingly, they are more likely to conduct cell-level research as well. Both a pro-patenting and a pro-theory ethic thus move the scientist toward small-object research, even though the former is in an applied direction and the latter in a basic direction.



a. Positive numbers indicate a net average rise – and negative numbers a net mean decline – in the chance the scientist will conduct applied rather than basic research or large-object rather than small-object research. Figures take into account shifts into and out of organism research.

Figure 1. Net Average Impact of Funding Source on Probability of Conducting Research at the Indicated Basicness and Object Size.[a]



a. Positive numbers indicate a net average rise – and negative numbers a net mean decline – in the chance the scientist will conduct applied rather than basic research or large-object rather than small-object research. Figures take into account shifts into and out of organism research.

Figure 2. Net Average Impact of Indicated Professional Norm on Probability of Conducting Research at the Indicated Basicness and Object Size.[a]

By way of summary, Figure 1 gives each funding source's and Figure 2 the scientist's professional norm's net average impact on research basicness and object size. Positive coefficients indicate a net rise in the chance of encountering an applied rather than basic topic or a large-size, such as an ecosystem, rather than small-size, such as molecular, research object. Among funding sources, state governments and industry create the largest average impulses toward applied and large-object research. Shifting one percentage point of the scientist's funding from the National Science Foundation to biotechnology firms creates a net increase of 0.61

percentage points in the likelihood the scientist will engage in applied research. Industry funding also increases the likelihood he will engage in large-object rather than small-object research. Neither state nor USDA funding has an appreciable net effect on research object size.

Policy Implications

The importance of academic research, particularly at the basic and translational but even the development stages of the genetic engineering process, is so great that any examination of GE's future is incomplete without considering how professors decide what to study. The rate and character of genetic engineering research in agriculture depends on the balance achieved between basic and applied, excludable and nonexcludable, and micro- and macro-object investigation. In universities at least, these characteristics in turn depend on the scientist's human capital and institutional culture, professional norms, and funding sources. Our study strongly suggests professional norms have at least as great an influence as do any of these other factors.

Nevertheless, industry funding pushes academic bioscience research strongly toward the applied end of the research spectrum and toward organism or ecosystem level work. In both respects, industry support thus militates against foundational gene-modification research and toward the organism and ecosystem levels at which that research is applied and controlled. USDA and state funding has, albeit less sharply, the same effect. Taken together, these findings suggest both the private and public sector are effective in encouraging university organism and ecosystem research. Solutions to some GE crop challenges, such as weed resistance and climate change mitigation, thus can be addressed in both sectors, individually or collaboratively. In contrast, aggregate public funding boosts basic and cell-level research only because NSF and NIH push substantially in those directions.

Much has been surmised in the popular literature about money's influence on the direction and content of academic biotechnology research. The concern is justified because money source does affect what academics do. However, the relationships are more complex than often portrayed. Two factors mute the money-effect worries. The first is that professors' academic norms, influenced by their personal interests and the culture in which they work, appear to be more important than funding-agent preferences, militating against undue industry influence in public science. Understanding the factors affecting these norms should thus be a high priority in social science research. The second is that, although the privately sourced share of university funding has risen as a share of total research resources, it remains a small proportion of the total pie. In any event, USDA and state funding have much the same effects as industry. Furthermore, we have found in our analysis that public and private finance tend to compete with one another in the university laboratory, each tending to push the other away. Perhaps the most important trend to watch is the generational rise of the patenting and licensing ethic in U.S. universities (Stuart and Ding 2006), which likely is taking us toward greater commercial control of life-science technologies.

For More Information

Buccola, S., Ervin, D. and Yang, H. (2009). Research Choice and Finance in University Bioscience. *Southern Economic Journal* 75(4):1238–1255.

National Research Council. (2010). The Impact of Genetically Engineered Crops on Farm Sustainability in the United States. Washington, D.C.: The National Academies Press.

Stuart, T., and Ding, W. W. (2006).When do Scientists Become Entrepreneurs? *American Journal of Sociology* 112, pp. 97 -144.

Sharmistha Nag (snag@ncaer.org) is a postdoctoral fellow at the National Center for Applied Economic Research, New Delhi, India. Hui Yanghui (yang@bankofamerica.com) is a vice president, Risk Capital & Portfolio Analysis, Bank of America, San Francisco. Steven Buccola (sbuccola@oregonstate.edu) is the corresponding author and a professor in the Department of Agricultural and Resource Economics, Oregon State University. David Ervin (ervin@pdx.edu) is *a professor in the Departments of Economics and Environmental Management, Portland State University.*

The authors would, without minimizing others' contributions, would like to thank Anita Azarenko, Chair of the Department of Horticulture at Oregon State University, for her assistance with this analysis. This study was supported by a grant from the U.S. Department of Agriculture under IFAFS Agreement No. 2001-52100-11217.