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# ***Agricultural Biotechnology: How Big is it Globally?***

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Transgenic crops were first grown commercially on a large scale in 1996 when 1.7 million hectares (Mha) were planted. During the intervening years, the area in transgenic crops grew to 67.7 Mha in 2003. This rate of adoption of a new technology is remarkable, but similar to rapid adoption of other breakthrough technologies of the past (James, 2003). While many different types of transgenic plants have been grown experimentally, relatively few have been grown commercially, and only soybean, maize, cotton and canola are grown on a large scale. The limited number of transgenic crops grown, and their concentration in just a few countries, is a reflection of the resistance shown by consumers in some parts of the world to this new technology (Alston, 2004).

Each year since transgenic crops were first planted, it has been anticipated by some that the adoption of this technology will plateau and eventually decline because of consumer resistance and governmental barriers in some regions of the world. This does not seem to be happening and an analysis of recent trends suggests that widespread adoption will continue to expand beyond the United States. The United States remains the largest producer of transgenic crops, with more than half of the world-wide area in 2003. Rates of adoption of transgenic crops in some developing countries, however, have been rapid. Argentina was one of the early adopters of herbicide-tolerant soybean. In 1996–1997, 1% of the crop was genetically modified (GM), but by 2001–2002 more than 90% of the crop was transgenic. An even more-rapid adoption of transgenic maize has occurred in Argentina (Trigo and Cap, 2003). Approval for planting of transgenic soybean in Brazil was given in 2003, and it was conservatively estimated that more than 3 Mha would be planted in 2003–2004 (James, 2003).

Farmers in China planted transgenic cotton for the first time in 1998 and by 2001 approximately 31% of that crop was of GM cultivars. However, these figures do not necessarily reflect how rapidly growers have adopted this technology. The commercial production of transgenic cotton began in a few provinces in the Yellow River cotton region. Within three years it represented 97% of the crop in Hebei Province and 80% in Shandong Province. Introduction of transgenic cotton occurred later in other regions. Cotton farms in China are small; it is estimated that *Bt* cotton had been adopted on more than 3.5 million by 2001 (Pray *et al.*, 2002).

Transgenic crops are slowly being introduced in other countries. In 2003, five countries each had more than 1 Mha of transgenic crops (United States, Argentina, Canada, Brazil and China) and another five had between 50,000 and a million ha (South Africa, Australia, India, Romania and Uruguay). Small plantings of transgenic crops have occurred in another eight countries, most of which are not likely to join the group of major producing countries soon (James, 2003).

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Resistance in some parts of the world to transgenic food products is slowing the spread of both the type of transgenic crops produced and the locations in which they are grown (Alston, 2004). There has been much public discussion concerning the relative costs and benefits of the technology, but unless consumers are confident that benefits substantially outweigh the costs, spread to other crops and countries will be slow. Where farmers have been given the opportunity to make a choice, however, adoption has been rapid. This is true for both large-farm producers in the United States and smallholders in China and South Africa. A number of studies have indicated that the rapid adoption of this technology is primarily driven by economic advantage. Economic incentive is the most important driver of non-mandated change, so it is not surprising that this has occurred.

### ECONOMIC ADVANTAGES OF GM CROPS

The type of economic advantage provided by the technology has varied from region to region. A survey of literature-source data obtained from US growers regarding farm-level advantages of *Bt* cotton and maize and herbicide-resistant soybean indicated that, in most cases, the growers used less pesticide and had higher profits than they did using comparable conventional technology (Marra *et al.*, 2002). It was reported that there was a profit advantage for the farmer of from \$16 to \$173/acre, including the technology fee, for growing *Bt* cotton. A reduction in pesticide sprays of from 1.3 to 3.4 spray events per season was a major reason for this economic advantage.

A more comprehensive survey in China over a three-year period demonstrated the same trend among smallholder farmers (Huang *et al.*, 2002a; Pray *et al.*, 2002). This study documented the reduction in pesticide use by farmers who adopted *Bt* cotton to be 24–63 kg/ha. To put these savings in perspective, it was reported that in 2001, adoption of *Bt* cotton in China resulted in a reduction of 78,000 tons of formulated pesticide, the equivalent of about 25% of the total pesticide use on all crops in China in the mid-1990s (Pray *et al.*, 2002). The net economic advantage to Chinese growers of *Bt* cotton was estimated at approximately \$500/ha compared with the growing of non-*Bt* cotton. A similar economic advantage—due to reduction of pesticides and increased yields—was reported for farmers with smallholdings in South Africa (Ismael *et al.*, 2002).

The economic advantage of adoption of herbicide-resistant soybean in Argentina appears to be primarily the result of energy savings from switching to no-till cultivation methods, which facilitated double-cropping soybeans with wheat (Trigo and Cap, 2003). In addition, the patent protection for Roundup has expired resulting in competitive pricing of this herbicide; it is estimated that the price in 2001 was less than 30% of the price paid when Monsanto held the patent. The authors of this study indicated that the cost advantage of transgenic soybean to growers was about US\$20/ha, primarily due to energy-cost savings from the more effective weed-management strategy.

These various examples from different parts of the world demonstrate that economic advantage to the farmer resulted in rapid adoption of the technology. The particular nature of the economic advantage varied from country to country, but generally was associated with a reduction in the use of pesticides or cost savings that resulted from changing pesticide-use practices.

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## RESEARCH INVESTMENTS

Investments in research represent confidence in economic returns. This is particularly true for investments in the applied sciences, such as agriculture. Agricultural research was the first publicly supported research endeavor probably because it was widely recognized in the agrarian world of the time that providing the funds for that research would have immediate, important paybacks. During the past century, the development of agricultural machinery, processed foods and beverages, synthetic fertilizers, hybrid seed, and pesticides opened the doors for agricultural research investments by for-profit companies. Within the past fifty

years there has been a significant increase in agricultural research by the private sector relative to that funded by the public sector. Private-sector agricultural research in the United States more than tripled in constant-value dollars between 1960 and 1995 (Shoemaker, 2001).

The first major shift in agricultural research from the public to private sector occurred with the development of pesticides. While pesticides were originally a product of public research, today, essentially all pesticide-development research occurs in private laboratories. Shifts are also occurring in traditional plant-breeding programs: in 1980, 70% of the soybeans planted in the United States were public-sector varieties whereas in 1997 it was estimated that only 10–30% of the soybeans were public-sector varieties. Public-sector cotton seed declined from 37% in 1975 to 1979 to about 7% in 1997. Maize-seed sales in the United States in 1997 were dominated by four private companies, with a combined market share of 69% (Shoemaker, 2001). All major US commercial transgenic crops were developed by private seed companies. This shift to private-sector agricultural research has certainly accelerated with the advent of agricultural biotechnology, and because of the rapid change in the relative roles of public- and private-sector agricultural research, unresolved stresses are occurring. It is not surprising that a recurring theme in discussions about agricultural biotechnology relates to social/economic issues associated with for-profit companies seeking payback on their research investments.

Public institutions continue to actively invest in agricultural biotechnology research, which contrasts with their withdrawal from pesticide research and development. Although private investment in agricultural biotechnology exceeds that of public-sector investment (55%:45%), public-sector investment is growing throughout the world (Huang *et al.*, 2002b). Even in countries such as Japan, where consumers are opposed to transgenic foods, significant investments are being made in agricultural biotechnology research. European scientists play major roles in the research that enables agricultural biotechnology product development and they continue to field-test transgenic crops in a public environment hostile to the technology. China's investment in agricultural biotechnology has increased rapidly, and if proposed increases in spending come to fruition, it will account for about one-third of the public-sector investment worldwide. The payback in China for investment of public funds in transgenic cotton was repaid in social benefits by only the second year of commercial production (Huang *et al.*, 2002b). The anticipation of this type of economic return on investment is what appears to be driving the increasing investment in agricultural biotechnology by public entities, even in those countries that do not permit commercial production of GM crops.

Although many have suggested that the public resistance to agricultural biotechnology is similar to the resistance that resulted in the cessation of expansion of nuclear power in the United States, such comparisons are superficial at best. The growth in research and academic program investments in agricultural bio-

technology is not typical of those of an industry in the throes of death. Unlike the nuclear-power industry, which had only a single product to offer, there are unlimited possible uses of transgenic technology in agriculture. Some of these are clearly not suitable for field release or food use, but there are many that will meet strict regulatory standards and provide significant economic and social benefits.

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## HUMAN HEALTH ISSUES

One of the early questions raised about methods used to create transgenic crops was whether there would be increased health risks for consumers, unique to the technology. This is a much-researched topic that has yielded no clear evidence of negative health effects associated with those GM crops that have been adopted. Therefore, little of value can be added here except to point out that most reviewers of the topic have concluded that the methods *per se* do not create a risk (Kaeppeler, 2000). It is clear, however, that each new product should be assessed for its risks and benefits, as should be true for any new food product.

Another way to look at the health effects of currently grown GM crops is to examine if any positive, rather than negative, health benefits have resulted from their adoption. One of the most obvious considerations is that related to the shift in pesticide use associated with *Bt* and herbicide-resistant crops. The concern about the toxicity of pesticides has been a major driver in the growth of the organic food industry; it is obviously a topic of great public interest and because of the possible toxicity associated with the consumption of most pesticides, their residues in food are carefully regulated.

### *Pesticide-Associated Illnesses*

In China, more pesticides per hectare are used on cotton than on any other crop (Huang *et al.*, 2002c). Significant reductions in use of pesticides have occurred in that country as a result of the adoption of *Bt* cotton (Pray *et al.*, 2002), with concomitant reductions in occurrence of farmer illness from pesticide exposure. Over the three-year period of 1999 to 2001, between 12% and 29% of the farmers who grew non-*Bt* cotton reported becoming ill because of exposure to pesticides. In contrast, during the same period, only 5% to 8% of farmers growing *Bt* cotton reported becoming ill due to pesticides (Huang *et al.*, 2002a). Clearly, reduced exposure to pesticides resulted in dramatic health benefits for the estimated 3.5 million farmers with smallholdings in China who had adopted *Bt* cotton by 2001 (Pray *et al.*, 2002).

## *Pesticides in Drinking Water*

This reduction of insecticide use, and the replacement of more-toxic, persistent herbicides by a less toxic, easily degraded alternative, should result in public-health benefits. Pesticides are common contaminants of public water supplies. The US national primary drinking water standards lists thirty-three items to be regulated for their presence in drinking water; twenty-three of these are pesticides or their breakdown products (OTA, 1995). The herbicide atrazine is one of the more common and toxic contaminants of drinking water in agricultural regions where it is used (Barbash *et al.*, 2001). Replacement with less-toxic, readily degraded glyphosate should result in fewer problems of public water-supply contamination by atrazine (Barbash *et al.*, 2001). Likewise, reductions in the use of organophosphate insecticides where *Bt* crops are grown should also reduce the danger of contamination of drinking water.

## *Mycotoxins in Food*

There is growing evidence that *Bt* maize has reduced amounts of mycotoxins in the grain than has non-*Bt* maize. Fungi capable of producing toxins are ubiquitous on crops. Many are weak pathogens and grow on plant surfaces or in wounds. Once established in wounds, they are able to penetrate adjacent living plant tissue. Fungi produce a wide array of secondary metabolites, some of which are toxic and/or carcinogenic to humans and animals. Among the most potent is a closely related group of secondary metabolites known as aflatoxins (Payne and Brown, 1998). These and other mycotoxins, such as the fumonisins—formed in plant tissues including grain—are important health threats and stringently enforced regulations limit their presence in food. In many parts of the world, particularly in Africa, these mycotoxins are responsible for serious health problems since much of the food consumed is not inspected for mycotoxins (Bankole and Adebajo, 2003; Fandohan *et al.*, 2003).

*Bt* maize contains less of the fumonisins than does non-GM maize probably because there is less predation by insects (Munkvold, 2003). Fumonisin, produced by *Fusarium* spp., cause a variety of health problems in animals, including humans (Bankole and Adebajo, 2003). The extent of the reduction of fumonisins in *Bt* maize compared with non-GM maize surprised researchers (Munkvold, 2003). It appears that the reduction is the consequence of fewer fungi growing in grain damaged by insects, particularly the European corn borer. Bakan *et al.* (2002) reported that experiments in Spain and France showed that grain of *Bt* maize had 4- to 10-fold less overall fungal presence than did non-GM varieties, as determined by the relative amounts of ergosterol, a fungal membrane component, in the grain. In these studies the amount of fumonisin B1 was significantly reduced in *Bt* maize. In summarizing the results of thirteen studies where fumonisin content of *Bt* and near isogenic non-*Bt* maize were compared, Munkvold (2003) reported that in eleven of these studies, significant reductions of fumonisin content were reported in *Bt* maize. Magg *et al.* (2002) found only slight reductions in

the amount of fumonisins in *Bt* maize grown in central Europe and suggested that *Bt* maize may not be effective in reducing fumonisins under these growing conditions. Munkvold (2003) indicated, however, that fumonisin content is generally negligible in maize grown in higher latitudes; the most common maize-ear disease of that region—gibberella ear rot—is not associated with insect damage. Similar consistent reductions of aflatoxins in *Bt* maize have not been reported, probably because heat and water stress are more important factors in the development of the fungi responsible for aflatoxin contamination than is insect damage (Munkvold, 2003).

Developed countries have strict standards for the amounts of mycotoxins allowable in food. Foods that contain mycotoxins, such as maize, peanut and other nuts, and dried fruits generally do not represent a large portion of the diet of consumers in developed countries, so the benefits of *Bt* maize, and future transgenes that reduce mycotoxins in food, will not be as important as they are to developing countries where these foods represent a much larger part of the diet, and where there are less-developed regulatory and inspection programs (Bankole and Adebajo, 2003). It is ironic that the narrow interpretation of the precautionary principle with the intention to protect the health of consumers in some developed countries has created an atmosphere whereby solutions to serious health and economic problems in developing countries are stymied (Otsuki *et al.*, 2001).

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## ENVIRONMENTAL ISSUES

A variety of concerns have been expressed regarding the impact of transgenic crops on the environment. Primary among these is that unwanted genes may become fixed into populations of wild species. This is not a new problem since many of our crops have the potential to breed with related wild species, but we obviously do not want to continue to spread plants and animals around the world in ways that may disrupt local ecosystems. Most of the plants and animals that our ancestors domesticated and that we use to feed the world did not evolve where they are grown today; not surprisingly, some of these have become weedy. The issues related to environmental impacts of agricultural biotechnology thus can be considered as a subset of the issues related to all invasive species, *i.e.* will this technology create new or unique problems that may cause environmental or economic challenges?

The primary question regarding agricultural biotechnology is not whether GM crops can have negative impacts on the environment, but whether or not there is something unique about the technology that creates a need for them to be separately regulated. The Ecological Society of America has considered this issue and concluded that the technology does not create unique risks, but that there are potential risks from products of the technology that must individually be evaluated (Snow *et al.*, 2004).

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Our traditional genetic manipulation technologies, *i.e.* selective breeding and induced mutation methods, create products that have potential risks. The southern corn leaf blight of maize was a consequence of the widespread use of a rare mutation in maize, the cytoplasmic Texas male sterile trait. This useful trait for the breeding of hybrid maize unintentionally created plants that were uniformly susceptible to a previously unknown fungal disease (Bekele and Sumner, 1983). In essence, the use of this naturally occurring gene in traditional breeding programs created a new plant-disease problem. It is impossible to foresee such consequences, and they are clearly not unique to a particular technology. Other examples similar to the southern corn leaf blight incident are known, and they collectively reinforce the reality that risk is associated with any change.

The key question is whether or not the benefits associated with widespread adoption a new product are worth possible unknown risks. Experience to date would suggest that the environmental risk associated with the current generation of GM crops has been minimal and that positive environmental benefits have come from their adoption.

Decreased use of insecticides and the switch to less-toxic herbicides have been significant benefits from the adoption of the first generation of GM crops. These are important not only for human health but also for the environment. Agricultural chemical use is widely considered to be detrimental to the environment, and reduction in use of these chemicals or change to less-toxic or less-persistent chemicals is a public-policy issue in many countries (NRC, 2000). The data documenting pesticide-use changes illustrate the impact that GM crops have had in meeting these public-policy goals. In Argentina there has been an 83% reduction in the use of herbicides of toxicity class II and a total elimination of the use of those of toxicity class III. While there was an increase in the amount of herbicide used, the increase was in the lowest toxicity class. Associated with this change in herbicide use was the adoption of no-till practices on over 9 Mha of double-cropped soybean and wheat. The net benefits from adoption of GM soybean in Argentina were thus decreased energy use, less soil erosion by adoption of no-till practices, and a shift to a less toxic and rapidly degraded herbicide (Trigo and Cap, 2003).

A careful study of pesticide-use changes in China after adoption of *Bt* cotton showed similar positive environmental benefits. Huang *et al.* (2002a, c) concluded that pesticide use with *Bt* cotton decreased sharply compared with non-*Bt* cotton cultivation, in some regions by 70% to 80%. This reduction is an important accomplishment since it has been suggested that farmers in China overuse pesticides to optimize yield and reduce labor inputs on their small-farm plots (Widawsky *et al.*, 1998). Host-plant resistance as a means to control insects and disease is recognized as a much more environmentally friendly approach, and needs to be encouraged where such resistance is available (NRC, 1996).

The trends in pesticide use reported above suggest that there is hope for further significant changes in amounts and types of pesticides used as more GM crops are adopted. In the United States, it has been public policy to encourage alternatives to pesticide use in agriculture. California, which accounts for 22% of the national pesticide use, has led this effort, in part by requiring adoption of the world's most comprehensive reporting system for pesticide use. Yet despite significant efforts to reduce California's pesticide use with non-biotech methods, an examination of the data showed no change between 1993 and 2000; the same was true for pesticide use in the rest of the country (Epstein and Bassein, 2003). The impact of adoption of GM crops would not likely be noticed on this scale of reporting since herbicides account for the greatest proportion of pesticides used (68%), and the amount of herbicides used is not expected to drop with adoption of GM crops; a shift to lower-toxicity herbicides is the expected outcome. Also, the greatest use of pesticides in the United States is on high-value crops with which no GM alternatives are commercially available.

Pesticide use is not uniform around the world; the highest relative amounts applied per hectare are in Japan and the European Community (Parris and Melanie, 1993). It is unfortunate that the regions of the world that apply the most pesticides have taken the leadership in opposing adoption of agricultural biotechnology and thus have slowed the adoption of a technology that has the potential to substantially reduce the amounts of toxic, persistent pesticides used in the world. Parris and Melanie (1993) suggested that high use of agricultural chemicals in these regions is the result of the relative political power of farmers who have successfully blocked the adoption of stringent environmental policies that would limit the use of agricultural chemicals. There is ample evidence for the adverse human-health and environmental costs associated with the use of pesticides (Low *et al.*, 2004). A proven technology to reduce toxic pesticide use is available and would likely be adopted if the precautionary principle were used with a broader perspective in policy decisions (Levidow, 2003).

## CONCLUSION

The first large-scale planting of GM crops was in 1996. Since then, the rate of adoption of the relatively few types of GM crops available has been dramatic, increasing to almost 70 Mha planted in 2003. Although the largest proportion of

GM crops is grown in the United States, many other countries of the world plant them. The very rapid adoption of available GM crops in developing countries such as Argentina and China attest to the economic advantages to farmers. The particular economic driver of adoption varies between countries, but they are clearly not limited to large farms; more than 3.5 million farmers in China grow Bt cotton on small holdings (Pray et al., 2002).

One of the first concerns expressed was that GM technology would create genetic changes that could pose health risks to consumers. Considerable investigation of this issue, and years of experience with the technology, have revealed no evidence for such risks (Kaeppler, 2000). Each product of the technology, however, needs to be assessed for potential health risks, particularly possible allergenicity (Taylor and Hefle, 2001). This scrutiny should not be limited to foods created by transgenic means. There is strong evidence that adoption of currently available GM crops will have positive health benefits, such as reducing pesticide poisoning of farm workers and reducing the exposure of consumers to highly toxic and carcinogenic mycotoxins (Munkvold, 2003) particularly in the developing world.

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Although environmental risks are associated with some of the possible uses of the transgenic technology, it is the product, not the technology, that presents the potential risk (Snow et al., 2004). Again, each product must, therefore, be carefully studied for its potential risk before it is widely adopted. This is similar in principle to the assessment of any risk to the environment that must be conducted prior to an action, such as the movement of plants and animals into a new area. On the other hand, adoption of some GM crops has resulted in a positive impact on the environment. Pesticide use in some areas has decreased as a consequence of the adoption of Bt varieties; toxic, persistent herbicides have been replaced by less toxic easily degraded alternatives, and soil and energy have been conserved by taking advantage of the GM technology to adopt no-till cultivation methods.

Although the adoption of GM crops has been very rapid in countries that have approved them, there has been resistance in many other countries, particularly in Japan and the European Community. The complexity of the social issues driving this resistance is illustrated by the fact that the countries most resistant to adoption of the technology are also by far the largest users per hectare of pesticides

(Parris and Melanie, 1993), which are known to cause health and environmental problems. A systems-level approach to evaluation of the relative value and risk of GM technology would entail studies of how this technology might reduce pesticide use in intensively managed crops, conserve soil by adoption of reduced tillage methods, or reduce human health risks associated with use of pesticides and consumption of mycotoxin-contaminated foods in developing countries. These analyses could be done using the currently available GM crops without even considering all of the other possible benefits that can be derived from adoption of new products of this technology. These comments are not meant to suggest that there does not need to be close oversight and evaluation of new products of GM technology, only to suggest that we need to do just that, *i.e.* allow the evaluation and adoption of products derived from biotechnology.

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