Environmental Benefits and Sustainable Agriculture through Biotechnology

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Introduction

Many scientists and farmers are optimistic and enthusiastic about the prospects of using biotechnology to improve yields and nutritional value of crop plants while decreasing the input of chemical pesticides. However, the safety of genetically engineered plants for humans and the environment remains a hotly debated issue. Controversial reports of some genetic therapy trials, as well as the memory of environmental catastrophes which resulted from well-intentioned interventions, such as the effects of DDT and the explosive growth of the introduced plant kudzu, have engendered caution about the applications of biotechnology.

Potential benefits associated with genetically engineered crops were highlighted in the introduction to the forum. The addition of one or a few genes to a plant may make it more productive, more nutritious, more tolerant to environmental stresses such as drought, and more resistant to disease and pests. In these ways, biotechnology can enhance the efficiency and therefore the productivity of agriculture, while at the same time reducing some of the detrimental effects (such as pesticides) of modern agriculture on the environment.

Biotechnology offers benefits for certain crops, but some scientists and other citizens are concerned about long-term and unintended effects. Genes introduced into crops to enhance insect or herbicide resistance may be transferred to nearby weeds if they are closely related to crop plants. In time, pests will most likely develop resistance to engineered traits, like production of the *Bacillus thuringiensis* (Bt) toxin, thereby making these new plant varieties less useful and reducing the effectiveness of externally applied Bt for organic farmers. Some non-target species may be affected by the genetically altered crops. Finally, there is always a risk in depending on one or a few varieties of a crop plant because of the lack of genetic diversity. If climatic changes occur or a plant virus mutates, then a wheat or corn crop may fail because all the plants are equally susceptible.

Genetic engineering is an accelerating technology, and various safety issues need to be addressed while we continue to develop new varieties and technologies to make agriculture more productive and provide sufficient food for the world’s growing population. Researchers need increased funding to assess problems which may be associated with transgenic crops and management strategies to avoid or ameliorate them.

Methods in biotechnology

Conventional plant breeding, as most people envision it, involves careful assessment of different plants in a field or varieties of plants from different geographical areas, followed by selection of those with desirable traits for future breeding. However, when specific characteristics are selected for, a certain amount of “genetic baggage” accompanies them and this baggage may include some genes with detrimental effects. So the process of producing a useful new variety of crop plant may involve many generations of crosses and back crosses. In fact, conventional breeding has inadvertently produced some undesirable taxa, e.g. Africanized honey bees and a weedy rye plant.

Increasingly, in recent decades more sophisticated techniques—including mutagenesis, protoplast fusion, and embryo rescue—have been used to produce new plant varieties which might be impossible to produce naturally. One might consider genetic engineering one step further in plant breeding where one or a few genes are transferred from one organism to another. Usually the inserted genetic material contains: (a) a gene of interest such as that coding for an insecticidal toxin from *B. thuringiensis*; (b) a marker gene such as antibiotic resistance to select plant cells with the new genetic material; and (c) a promoter gene, often a viral promoter which causes the new gene to be expressed all the time (constitutively). Each of these components should be evaluated for safety. To date, they all have been, and there is no evidence that any of them pose a threat to human health.

Control of gene expression in plants is a complicated matter. A variety of regulatory genes and proteins specify which genes are turned on, in which tissues and at what times. Transposons may also be a major factor controlling gene expression. Within the next 10–20 years we will acquire a better understanding of the complexity of these control systems and genetic engineers will have a "tool box" to control expression of inserted genes so they are only active in certain tissues or at certain times in a plant's life cycle. Inserted genes could also have an inducible regulatory system, i.e. genes which are only expressed in response to certain environmental conditions or when some non-toxic activating substance is sprayed on the fields. Such fine tuning of gene expression could enhance the effectiveness of engineered genes and diminish the likelihood of detrimental effects on non-target species and the development of resistance in pest species.

Data on crop protection/yield increases

Data on the actual field performance of several genetically engineered crop varieties (canola, corn, cotton, potatoes, soybeans) were provided by university, commercial, and government researchers, as well as by some farmers who have grown both conventional and genetically engineered crops. Generally, they reported that although the cost of the new resistant seeds is greater, the savings in expenditures for herbicides and pesticides offsets it, and farmers reap a greater net profit with the genetically modified (GM) plants. Growing GM plants is often easier because of the decrease in the number of different pesticides used and the number of applications required.

Several varieties (events) of corn have been engineered to contain genes coding for different forms of Bt toxin which kills European corn borers. Data indicate that 45% of farmers had higher yields in fields of Bt corn compared to conventional corn in 1998, and nearly 26% of farmers growing Bt corn reported a decrease in pesticide use. In most years, growing Bt corn produces a net gain in income, but this may not be the case in years when corn borer populations are lower and the extra cost of planting Bt corn (about $15/acre) is not offset by relatively higher yields. Central Illinois farmers have been told that planting Bt corn should pay off in 7 out of 10 years.

In addition to preventing direct insect damage to corn, the introduced Bt genes in some corn events were found to significantly depress the incidence of *Fusarium* ear rot (a fungal infection) which is spread by corn borers. The *Fusarium* molds produce several harmful mycotoxins, the most important of which are the fumonisins. Depending on insect populations and climatic conditions, between 0.4 and 10.5% of midwestern corn contains >5 ppm of fumonisins. Use of Bt corn or other insect-resistant corn could decrease levels of these carcinogenic mycotoxins by decreasing physical damage that opens the plant to these secondary infections.

Even when yields are higher for Bt corn and pesticide costs are lower, market forces can depress the price of corn when there is an abundant harvest as in 1998. One final consideration which must be weighed by farmers is the consumer acceptance of genetically engineered corn. If some consumers and food processors do not want to use Bt corn, then Bt and non-Bt corn may need to be segregated, and non-Bt corn may be worth a premium. Therefore, a farmer's decision to plant GM corn or a conventional variety is not clear-cut.

Transgenic soybean varieties resistant to the glyphosate herbicide Roundup (Roundup Ready or RR soybeans) definitely provide benefits to farmers and in 1998 were planted on 60% of soybean acreage. Johnson grass is the primary weed in soybeans in the southern US, and it, along with other weed species, is very susceptible to Roundup. Although RR seeds cost more to plant, herbicide costs are greatly decreased and yields are the same as for conventional varieties of soybeans. Studies have demonstrated that farmers can save as much as $27/acre in overall growing costs with RR soybeans. In addition to these benefits, conventional soybeans require several applications of different herbicides during a growing season, whereas fields for RR soybeans can be treated just with Roundup.

Two types of transgenic cotton have been introduced: insect-resistant varieties with Bt genes and varieties which are resistant to herbicides, Roundup or bromoxynil. Herbicide-resistant varieties produce the same yields as non-transgenic plants; but herbicide use, normally 5.5–9 lb/acre, is reduced to approximately half that amount.

Bt cotton, introduced in 1996, is now planted on about 17% of US cotton acreage. However, in some areas such as Alabama and Arizona which have more severe problems with pink bollworm and tobacco budworm, up to 90% of the cotton planted contains Bt genes. In Alabama, cotton losses decreased from 30% in 1995 to <5% in 1996. Data indicate that insecticide use was much less for Bt cotton, and farmers earned a net profit of about $40 more per acre for the transgenic as compared to the conventional varieties.

New Leaf potatoes, genetically engineered to contain a gene for Bt toxin, are protected from defoliation by Colorado potato beetles and have a taste and yield similar to conventional Russet Burbank potatoes. However, aphids, which spread potato leafroll virus, are not affected by the Bt toxin; and therefore a new transgenic variety, New Leaf Plus was introduced commercially in 1999. Test plots in Washington state in 1998 indicated that farmers would save close to $90/acre on pesticide costs because they would need to apply 4 lb/acre less of active pesticide ingredients. Generally, fields required little or no pesticide spraying with the result that spiders and beneficial predatory insects were plentiful, yet aphid and mite populations were kept in check. In 1999, aphid populations peaked earlier and higher and some spraying was necessary. However, there was still a savings of $60/acre. Therefore, these transgenic potatoes can potentially significantly reduce chemical pesticide use although actual pesticide requirements may vary, depending on other factors.

Herbicide-resistant transgenic varieties of canola have greatly increased in popularity in the past few years, with an increase from 10% of Canadian canola fields planted with a GM variety (primarily Roundup Ready) in 1996 to 73% in 1999. Data from the Canola Council of Canada for the 1998 season showed that Roundup Ready varieties, when compared to conventional canola, produced greater yields (31 compared to 28.6 bu/acre) and greater profits ($86.40 to $52/acre). Fields with RR canola require only 1 herbicide application (instead of 2), and Roundup provides broader spectrum weed control. In addition farmers can plant canola late in the fall or early in spring (because the young plants will not be overgrown by weeds), and these early planting times allow flowering before the hot, dry July weather and ensure that the crop will be harvested before fall frosts.

Issues of Concern

Genetically modified crops definitely benefit farmers by reducing the number and amount of herbicides and insecticides needed, while preserving high yield. However, there are a number of issues of potential scientific concern related to the safety of foods from genetically modified crops and the effects of introduced genes on other organisms in the environment. There is no evidence that the antibiotic-resistance markers in plants will have a negative impact on human health or that commercial transgenic crops contain new allergens. Neither is it likely that introduced genes will confer weediness because that trait is usually a product of multiple genes. Since Bt toxins are specific for certain types of insects, they should have little impact on non-target species. And while there will be selection for resistance to toxins such as Bt in insect populations, there is no evidence that this will be different from what is encountered in traditional breeding practices.

In assessing potential risks from genetically engineered crops, one needs to gather data on the magnitude of the risk and the extent of exposure. For example, if the concern is transfer of introduced genes to non-crop plants by pollen, one should determine whether, in fact, pollen from the crop can cross with weedy relatives of the crop and measure the extent of pollen dispersal. Ironically, new crop varieties produced by traditional breeding are not scrutinized as carefully as GM varieties in the US, and therefore problems associated with them may not be identified. Canada has adopted the concept of a “novel variety” and requires similar testing for a novel crop, whether it is a product of genetic engineering or traditional breeding.

As many as 17 US crops have compatible weedy relatives growing nearby. Research has demonstrated that cultivated sunflowers, squash, and oilseed rape readily cross with and exchange genetic information with their weedy relatives. About 40% of weedy relatives growing within 3 m and 10% of those growing within 100 m of a cultivated sunflower field are actually hybrids between the cultivated and weedy forms. Rust resistance is one characteristic which has been transferred from cultivated to weedy sunflowers. Closely related weedy relatives of corn and soybeans do not grow in the US, but they may be present in other countries closer to the centers of origin of these species.

Although weedy relatives of rape are not a concern in Canada, data on outcrossing from fields of herbicide-resistant rape plants to non-resistant plants indicated that, with large fields and a strong wind, pollen could travel as far as 4000 km. However, the actual rate of outcrossing usually falls rapidly as distance from the field increases.

The consequences of transfer of an introduced gene from a GM crop to weeds must be evaluated for each situation. In some cases, for example, it could be a problem if herbicide resistance were transferred to weeds. In the case of insect- or virus-resistance genes, weeds may or may not be susceptible to the same organisms as the crop, and it may be that transfer of these genes to weeds may not confer any advantage to the weed.

Biodiversity in the natural world is important to humans for aesthetic reasons, as well as providing a source of products and genes which may be useful for evolutionary responses to changes in the environment. In addition, biodiversity is essential for an ecosystem to efficiently recycle and process nutrients, wastes, and gases. Since no organism exists without affecting its environment, one should anticipate that GM crops will have some effect on the organisms surrounding them. Whether these effects will be significant or deleterious should be investigated.

There are, of course, numerous examples of species, introduced to a new continent or island, which have caused havoc among the local flora and fauna. GM crops, however, are not very different from their non-transgenic predecessors. Nevertheless, some research has documented changes in the microbial communities associated with canola roots, alfalfa roots, and potato leaves in GM plants, compared to non-transgenic relatives. There is no evidence that these changes adversely affect the functions of the microecosystems around these plants. Indeed, simply planting a new crop in a field or changing the amounts of fertilizers and pesticides used will certainly affect microbial, as well as insect and weed, communities. Nevertheless, these studies point out that scientists should expect some changes with the increased use of GM crops and should monitor effects on microbes and other non-target organisms in order to prevent any untoward effects. More research is needed to: (a) identify factors that regulate weed and pest populations; (b) assess the interactions of crop-associated organisms; (c) determine how changes in microbial communities will affect the larger ecosystem.

Potential effects of introduced genes on non-target organisms have been highlighted recently by the experiments with monarch caterpillars. Although the Bt toxin is relatively specific, affecting only a few types of insects (not mammals or birds), some non-target species, including some beautiful and commercially harmless butterflies, are susceptible to this toxin. Experiments conducted by scientists in a number of locations this past summer sought to answer questions as to whether these butterflies would be harmed under real world conditions. These experiments examined: (a) concentration of Bt toxin in pollen grains and relative toxicity of Bt toxin in different GM varieties; (b) the decline of toxicity in pollen grains exposed over time to sunlight; (c) concentration of pollen grains on milkweed leaves (monarch caterpillar food) relative to distance from the corn field; (d) prevalence of milkweed in and near corn fields; (e) site preferences for monarch adult females for laying eggs. Results demonstrated approximately a 15-fold range in toxicity of pollen from different varieties, and this toxicity was gradually lost upon exposure to sunlight, and completely by day 9. Pollen grain concentration on leaves decreases as distance from the field increases, but nearly half the corn fields surveyed had milkweed growing in or near them. However, mother monarchs prefer to lay their eggs on exposed plants rather than on plants under a canopy of corn leaves, and prefer plants without high densities of pollen on the leaves. Toxicity requires pollen densities higher than that which naturally occurs outside the corn field. In fact, pollen (transgenic or not) actually adds to the calories and nutrients that increase larval weight. An overall conclusion from these preliminary results is that transgenic corn pollen has minimal impact on natural monarch populations, except for pollen from the most toxic Bt corn variety (#176)—which could be detrimental to monarchs if it were used in the monarch home range. However, #176 only accounts for 2% of transgenic plantings and is used outside the monarch range.

In fields of New Leaf Plus potatoes, researchers observed larger populations of predatory spiders, big-eyed bugs, and lady beetles and lower populations of aphids and mites. Since the Bt genes in the potatoes were suppressing populations of the major crop pest, Colorado potato beetle, little or no insecticides were sprayed on the fields and the predatory insects and spiders thrived and helped control the secondary pests. In this case, the Bt gene indirectly aided non-target species.

Pests are notorious for developing resistance to chemicals used against them, and we should anticipate that, in time, they will also become resistant to Bt toxins. Already there are some reports of tobacco budworm (a cotton pest) being resistant to one or more Bt toxins due to exposure to traditional Bt dusting.

The recommended plan for delaying development of insect-resistant populations involves a high-dose exposure and the use of "refugia" of non-Bt varieties. Of the 5 types of Bt corn grown in the US, 3 are considered high-dose and would kill a very high percentage of corn borers. Only a few, partially resistant individuals would survive. To prevent these individuals from mating with each other and producing a highly resistant population, refugia (located within the perimeter of a transgenic field) are sown with non-Bt seeds. The few resistant borers would likely mate with non-resistant borers, and their resulting offspring would be sensitive to Bt toxins. Without refugia, it is estimated that resistant populations would develop in 12 generations; with 10% of a field planted as a refuge, it would take 100 generations to develop a resistant population. It has been recommended that about 20% of corn fields be planted as refugia. An added advantage to refugia planted around the perimeter of a field would be a decrease in the drift of pollen from GM plants to weedy relatives or to plants which are a food source for non-target species.

Biotechnology shows great promise for crop plants in developing countries. New transgenic varieties could be resistant to locally important diseases and pests and have enhanced tolerance for drought or salinity. The nutritional content of staple crops, such as rice, could be improved by adding genes which increase production of vitamin A and some amino acids. These developments would improve the nutritional density of foods, thereby providing more and better food.

Some developing countries, such as Brazil, are hesitant to use biotechnology while others, such as Argentina, already have a high percentage of soybean and corn fields planted with GM crops. Several issues concern agronomists from developing countries—including the concentration of seed companies in a few hands and the lack of testing of transgenic crops in tropical environments where insect pests are different, more numerous, and grow faster. Will insect resistance develop faster in these countries? If most farms are small, how should refuge areas be provided? Social and economic consequences must also be considered when adapting a new technology to developing countries.

There are other concerns about transfer of these genetic engineering techniques to developing countries. The large companies which are currently producing transgenic crops are primarily interested at this time in crops planted over a large area in temperate climates. There are many "orphan crops" which are very important in tropical agriculture but which are not being developed by US biotechnology companies. Other impediments to the use of biotechnology internationally involve legal issues (patents and contracts) and trade secrets, including GURTS (genetic use restriction technologies), such as the infamous "terminator" gene. We need to democratize, decentralize, and diversify research into gene expression of crop plants and invent around some of the legal obstacles to use of biotechnology in developing countries.

Still other concerns involve the exportation of GM crops to developing countries. For example, the Chinese are planting Bt corn and cotton varieties which provide only a moderate dose of toxin against their major pest species, and they do not plan to plant refuges. Thus, they may see a rapid rise of Bt-resistant pests within a few years.

Politics

Many consumers are concerned about the introduction of GM foods into the human diet. To a large extent, this reflects a lack of knowledge about the processes involved in genetic engineering as compared to conventional plant breeding and the extensive testing being done to insure the safety of GM crops. But many people who do understand the technology are genuinely concerned about the possibility of introducing allergens into non-allergenic foods, the potential for misuse of this technology, the ecological effects of using GM crops and, on a religious level, the manipulation of nature and disruption of the natural order.

As yet, consumers, especially those in Europe, do not see GM crops as a benefit to themselves and therefore are cautious about supporting this new technology. GM corn and soybeans are not cheaper, more nutritious, or otherwise more useful to consumers. They might have lower pesticide residues or mycotoxins, but this has not been documented or publicized. Many groups insist that foods should be labeled so that consumers can choose what they are eating and decide for themselves if the potential benefits of GM crops outweigh the potential risks. In the UK, consumers actually preferred labeled GM-varietal Zeneca tomato paste over the non-GM variety. But when they realized that many of their processed foods contained Roundup Ready soybeans and there was no way to distinguish between soybean oil derived from GM and non-GM plants, many consumers were very upset. Farmers also want the choice of whether to plant GM crops or not and are frustrated by the European Union's moratorium on the one hand and the pressures from big business on the other.

Many scientists in academia and industry insist that these concerns are unfounded, but people have learned that political leaders and authorities are not always right. Several speakers at this meeting emphasized the need for dialogue and communication among scientists, consumers, government regulators, and producers on these issues. Whether or not people's concerns are scientifically justified, they must be addressed and discussed.

The BSE (bovine spongiform encephalopathy) crisis in England and recent scares in Europe about dioxin in Belgian foods, contaminants in Coca Cola, and the inclusion of sludge in animal feed in France have undermined trust in regulators and "big agriculture." Not only are regulators perceived as incompetent, but they also have obstructed public access to information about some of these crises so that people are even less inclined to trust them. The announcement that GM potatoes adversely affected the gastrointestinal tract of rats made for frightening newspaper headlines about "Frankenstein foods," despite the fact that the research was scientifically questionable. Environmental activist groups have taken up the cause, uprooting experimental fields and using scare tactics to stifle reasonable discussion of the issues.

Some trade experts in the US view this controversy and the moratorium by the European Union as an attempt to erect more trade barriers to protect European crops. But several Europeans at the conference insisted that it is not a trade issue, but rather a result of large multinational companies acting arrogantly and apparently dominating much of agricultural business and policy. Regaining trust will require more openness and genuine, reasonable discussion among all the parties involved.

Summary

As the world population expands, the demand for food will increase; and as people become more prosperous, they will want to improve the quality of their diet. These two factors will require an approximate doubling of food production in the next 50 years. Only a small amount of this increased food can come from opening up new land for farming and reducing post-harvest losses of foods. Biotechnology can be part of the solution by making agriculture more productive and reducing pre-harvest losses to insects, plant diseases, and competition with weeds. Improving the nutritional quality of staple foods and enhancing the resistance of crops to drought, cold, and salt will also increase productivity and upgrade human diets.

We need to adopt a global view of this issue, realizing that farmers in different countries and different environments face a variety of challenges. Biotechnology has much to offer these farmers. And both government and private sector groups should increase research efforts to find additional solutions for increasing the food supply while, at the same time, preserving the health of the environment and taking into account the social and political consequences of these changes in agriculture.

The Georgetown University Center for Food and Nutrition Policy (CFNP) analyzes complex issues in food and nutrition policy. CFNP provides instruction and mentoring in food and nutrition policy within the graduate program of the Georgetown Public Policy Institute. CFNP also organizes the Ceres Forum and the Demeter Dialogues where government, industry, academia and consumer groups can openly discuss issues in food and nutrition policy.

The Food Research Institute at the University of Wisconsin–Madison is a leader in food safety education, with research focusing on identifying and addressing food safety issues to provide information for science-based decision making.