PLANT BIOTECHNOLOGY: Advances in Food, Energy, and Health

Richard Hamilton, Richard B. Flavell, and Robert B. Goldberg

The world will need to produce more food, feed, and fiber during the next 50 years than in the entire history of humankind. The technological revolution created by genomics provides a unique opportunity to achieve this goal. Genetically engineered herbicide- and insect-resistant crops are delivering benefits through more affordable food, feed, and fiber that require fewer pesticides, conserve more soil, and provide for a more sustainable environment. And contrary to criticism, biotech crops have proven to be as safe as, or safer than, those produced by conventional methods. In the future, advances in agricultural biotechnology will result in crops that have improved tolerance to drought, heat, and cold; require fewer fertilizer and pesticide applications; produce vaccines to prevent major communicable diseases; and have other desirable traits.

Richard Hamilton *and* ***Richard B. Flavell*** *are, respectively, chief executive officer and chief science officer of Ceres, Inc., a privately held biotechnology company.* ***Robert B. Goldberg*** *is professor of molecular, cell, and developmental biology at the University of California, Los Angeles.*

Plants and agriculture have played an important role in the development and advancement of civilization. Plants provide sustainable supplies of food for humans, feed for animals, fiber for construction and clothing, medicines and drugs, perfumes, chemicals for industrial processes, energy for cooking and heating, and, most recently, biomass to meet the increasing demand for transportation fuels. Plants also play a major environmental role by preventing soil erosion, boosting levels of oxygen in the atmosphere, reducing carbon dioxide emissions from burning fossil fuels, and enriching soils with nitrogen, which they cycle between soil and the atmosphere.

AGRICULTURE IN THE 21ST CENTURY

If population growth continues as predicted, we will need to produce more food, feed, and fiber during the next 50 years than in the entire history of humankind. And we will need to do this on a decreasing amount of land that is suitable for agriculture and crop production.

This presents several major challenges for 21st-century agriculture:

- Crop yields need to be increased beyond the spectacular gains of the 20th century in order to meet increasing demand and save open space.
- Inputs required for intensive agriculture, such as water and fertilizers, need to be reduced.
- Crops need to be developed that can flourish in harsh conditions so that substandard land can be used to grow important crops, growing seasons can be extended, and yields are not decreased by drought, heat, cold, and other stresses.
- The environmental impacts of agriculture resulting from the use of pesticides, herbicides, and fertilizers need to be reduced. For example, crops need to be engineered that are resistant to pests, that take up nutrients more effectively from the soil, and that can out-compete weeds for water and sunlight.
- Food crops need to be optimized for human health and nutrition, providing essential vitamins, amino acids, and proteins to help eliminate malnutrition and disease.
- Novel energy crops need to be developed that are high yielding and that can be used as a renewable source of biomass for fuels to limit our dependence on a petroleum-based energy system.
- We need to go “back to the future” and engineer specialty crops that can be used as factories to produce chemicals and proteins for industrial and medical applications—for example, plastic precursors and vaccines to combat human and animal pathogens.

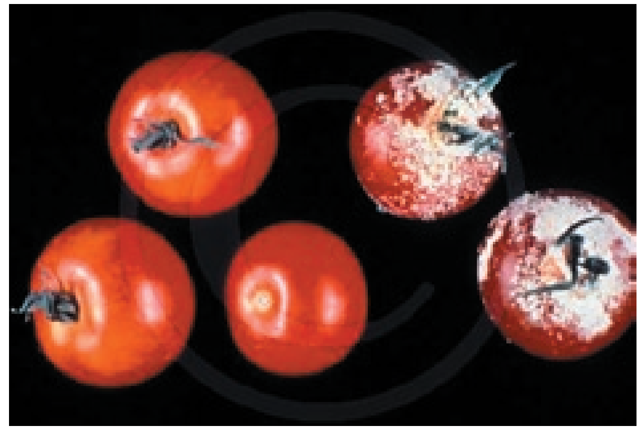
These challenges will require application of the most sophisticated breeding and molecular techniques available today, as well as the development of new ones. Nevertheless, there has never been a more exciting time for plant biology and agriculture, and the technological revolution created by the genomics era provides a unique opportunity to achieve these goals over the next two decades or sooner.

USING BIOTECHNOLOGY TO DEVELOP NEW CROPS

Most of the crops that we grow today did not spring forth from a mythical Garden of Eden and do not grow "naturally." To the contrary, most major crops were engineered by our ancestors thousands of years ago from wild relatives by selecting and breeding for traits that optimized crops for human use. These early genetic engineers learned how to recognize random mutations that appeared in wild plant populations and to use this genetic variability to create the food crops that we use today. For example, maize was bred from teosinte grass 10,000 years ago by selecting for a few genes that control cob size, seed structure and number, and plant architecture. Almost all of the crops that we use today, such as wheat, soybean, rice, potato, cabbage, broccoli, and tomato, were engineered in an analogous manner; that is by use of breeding technologies to create new gene combinations within a crop species and then selecting for better traits in the progeny.

The most significant innovations that are transforming agriculture are genetic engineering technologies that allow novel genes to be isolated, manipulated, and re-inserted into crop plants; the ability to regenerate almost any plant species from tissue culture into a fertile plant; and the development of high-throughput genomic technologies. The latter permits the mapping and sequencing of entire plant genomes and the identification of genes that control all plant processes, including those that can contribute to meeting the challenges of agriculture in the future, such as genes for disease resistance, drought resistance, seed size, and number.

At the genetic level, crop breeding depends on randomly introducing mutations, or genetic variability, into a plant's genome and then selecting from a large population the small subset of changes that result in a positive change. In the vast majority of cases, the genetic changes that are made are unknown. By contrast, genetic engineering affords a more precise alternative to breeding, and, because of its precision, it can be used to develop new, valuable traits in a small fraction of the time required to pursue the relatively imprecise techniques of breeding. Genes that have been characterized extensively can be introduced into crop plants in a precise and directed way in order to generate novel, genetically enhanced crops with traits that would not be possible to achieve using classical breeding procedures.



Volker Steger/Peter Arnold, Inc.

Mold-resistant bioengineered tomatoes and regular tomatoes over time.

THE GROWTH AND BENEFITS OF BIOTECH CROPS

The first genetically engineered crops developed in the early 1980s were resistant to herbicides and insects. Today, these two traits—herbicide and insect resistance—account for the majority of biotech crops. Over the past 20 years, there has been a worldwide effort to isolate genes that will provide a long list of traits that breeders, farmers, consumers, and industrialists have nominated for improvement in a variety of crops. Plant biotechnology and genetic engineering is now a major activity in the public and private sectors and is becoming a significant part of plant breeding on all continents. In fact, there has never been a more exciting time for agriculture because powerful genomic technologies make it possible to identify genes that have the potential for revolutionizing crop production over the next 50 years.

In 2005, we celebrate 10 years of biotech crop cultivation. During that period, 400 million hectares of genetically enhanced biotech crops have been grown. Biotech crops have been adopted by farmers all over the globe at a rate faster than any crop varieties in the history of agriculture—even faster than high-yielding hybrid maize during the last century. Since their introduction in 1996, the use of genetically enhanced biotech crops has grown at a rate of more than 10 percent per year, and in 2004, according to a report of the International Service for the Acquisition of Agri-biotech Applications, their adoption increased 20 percent. The main crops carrying new biotech genes are soybean, maize, cotton, and canola, accounting, respectively, for 56 percent, 14 percent, 28 percent, and 19 percent of the worldwide acreage for these crops. Together, they occupy nearly 30 percent of the global area devoted to these crops. In the United States, biotech soybean (herbicide resistant), maize (herbicide and insect resistant), and cotton (herbicide and insect resistant) account for

Betsy Blaney/AP/WWP

A cotton field.

approximately 85 percent, 75 percent, and 45 percent of the total acreage for these crops.

The United States is the leading grower of biotech crops, with more than 48 million hectares, followed by Argentina (16 million hectares), Canada (6 million hectares), Brazil (4.8 million hectares), and China (4 million hectares). The value of biotech crops is nearly $5 billion, representing 15 percent and 16 percent of the global crop production and seed markets, respectively. Biotech crops are delivering benefits through more affordable food, feed, and fiber that require fewer pesticides, conserve more soil, and provide for a more sustainable environment. In addition, the annual income of poor farmers in the developing world has increased significantly from the use of biotech crops, according to recent data from the United Nations Food and Agriculture Organization. Most of the value added has gone to those farmers rather than to the technology providers.

Concerns Limiting the Growth of Biotech Crops

Although crops produced by using biotechnology and genetic engineering have been adopted at warp speed and are the most tested and studied crops in human history, agricultural biotechnology is not without controversy. Opposition to the use of biotechnology and genetically engineered organisms derived from it is largely confined to Europe, where a small but vocal group of activists have fomented public opinion against the technology.

In an environment where non-biotechnology-related food scares over mad cow disease and dioxin have eroded the European public's confidence in the regulatory oversight of their food supply, activist groups have been able to generate substantial distrust of agricultural biotechnology. This distrust is misplaced: The hypothetical fears have failed to materialize after more than 10 years of safe use and more than 400 million hectares of cropland planted with genetically enhanced varieties. There are no known examples of ill effects of these crops in humans, and there are demonstrable environmental benefits. In fact, major studies, which have been published in peer-reviewed journals over the past five years, indicate that biotech crops are substantially equivalent to their non-biotech counterparts, that yields have been increased, that pesticide applications have been reduced, that large amounts of soil have been conserved, and that management practices have been successful in preventing or minimizing the resistance to insect-resistant crops. Although no technology is without zero risk, biotech crops have proven to be as safe as, or safer than, those produced by conventional methods.

Joerg Boethling

Genetically modified rice plants.

What About the Future?

In the next decade, further advances in agricultural biotechnology will result in crops that have improved tolerance to drought, heat, and cold; require fewer fertilizer and pesticide applications; produce vaccines to prevent major communicable diseases; have increases in seed size,

Scott Olson/Getty Images

Various corn hybrids are grown for use in ethanol production.

number, and nutritional content; and are able to regenerate in the absence of fertilization—fixing hybrid vigor. Crops will also be generated that are enhanced nutritionally to help alleviate malnutrition in the developing world. Currently, "golden rice 2" cultivars undergoing field testing are capable of delivering as much as 30 micrograms of beta-carotene, a precursor to vitamin A, according to a recent article by Jacqueline Paine and others. The authors estimate that this amount of beta-carotene should provide at least 50 percent of the recommended daily allowance for vitamin A in a typical child's portion of 60 grams of rice.

Beyond applications to increase production of food, feed, and fiber, biotechnology is making a substantial contribution to the energy area. Advances in biotechnology have enabled the production of large amounts of inexpensive cellulases that can be used to convert cellulose to simple sugars that can, in turn, be fermented into fuels such as ethanol. Recent estimates from the U.S. Department of Energy indicate that the United States could obtain 30 percent or more of its transportation fuels from biomass sources by 2020. Agricultural biotechnology has the potential to increase this number even further by enhancing biomass yield density, improving the processing characteristics of the biomass feedstock, and decreasing the need for agronomic inputs such as water, fertilizer, and pesticides.

Several key countries, notably the United States and China, are pushing ahead in agricultural biotechnology, making the necessary investments in research and development and providing a viable regulatory system for the introduction and commercialization of new bio-enhanced crops.

If we are going to create a new kind of agriculture in the 21st century that is both sustainable and productive with respect to food security and energy self-sufficiency, we will need to use all of the scientific tools and discoveries at our disposal, including biotechnology and genetic engineering, and to follow the continuous path of agricultural breakthroughs that have advanced human progress for thousands of years. ■

The opinions expressed in this article do not necessarily reflect the views or policies of the U.S. government.

BIOTECH BUGS

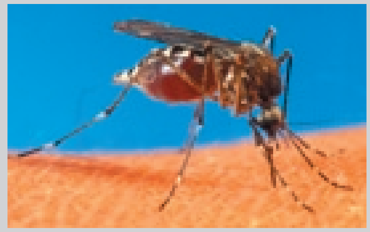
Following miracle cures and miracle foods, genetically modified (GM) bugs are generating a buzz in the scientific community as possibly the next "miracle" in the field of biotechnology. The successful application of GM insects could dramatically improve public health, particularly in developing countries, enhance agricultural production, and improve the natural environment, according to some scientists. It also could make one hesitate whether to hit a mosquito on one's neck because it can fight rather than carry a disease.

There are two types of GM insects under research: paratransgenic and transgenic. Paratransgenic insects are created by integrating a piece of DNA manipulated in the laboratory (referred to as the transgene) into the microbes that naturally inhabit their alimentary canal. Genes expressed in these microbes can alter the characteristics of the host insect. Transgenic insects are the product of the physical integration of transgenes into the chromosomes of an insect.

Genetically altering an insect so that all of its descendants will also be genetically altered requires that the initial integration of the transgene occur in the chromosomes of cells that will produce sperm or eggs (most insect reproduction is sexual). GM insects must have characteristics readily visible so scientists or other stakeholders can have a way of controlling them during research, for example, in order to separate male from female insects.

Scientists are working to develop a broad array of insects with new characteristics that could make them useful in fighting the spread of infectious diseases, controlling noxious weeds and insect pests, and producing pharmaceuticals. For example, honeybees can be genetically altered in a way that makes them resistant to diseases and parasites, and genetically engineered silkworms can produce industrial proteins for application in the creation of novel materials.

But no matter how productive those GM honeybees and silkworms can be, the greatest interest lies in GM bugs that may be able to save lives. Mosquitoes spread malaria, which infects 300 million to 500 million people and kills over 1 million annually, according to the World Health Organization. Chemical pesticides currently being used have negative effects on human health and the environment. And the emergence of insects resistant to many pesticides has undermined the efficacy of these pesticides.


AP/WWP/USDA

GM mosquitoes carry a promise of a clean and radical solution to the malaria problem. Scientists want to genetically modify male insects, which then could be bred, sterilized, and released into the wild to mate with females. Such skewed reproducing would lead to the eradication, or at least a dramatic reduction, of the natural mosquito population.

Another approach is to infiltrate genes for malaria resistance into the existing population of these insects. Introduced at high enough frequencies, such infiltration could decrease transmission of the disease, according to Anthony James, professor of biology and biochemistry at the University of California, Irvine.

The first confined field trials with different GM insects have already been conducted, and some projects are expected to reach full environmental release within three to five years. But a swarm of GM insects is nowhere near on the horizon. Technological and other obstacles will prevent scientists and businesses from wide-scale releases of transgenic bugs for at least 5 to 10 years or more, according to Luke Alphey of Oxford University's Department of Zoology.

Scientists and regulators also need to deal with uncertainty about the lasting effects these insects could have on ecosystems, public health, and food safety. What is more, the fact that insects do not respect borders creates international regulatory challenges that the world has never faced with GM crops. The United States and many other governments currently have no comprehensive policies on how transgenic insects will be reviewed, and international organizations are not involved yet in the relevant regulatory process. As a result, a 2004 report by the Pew Initiative on Food and Biotechnology concludes that the research threatens to outpace regulatory preparedness. The report says that if regulators and scientists want to have a clear set of rules in place before unconfined field testing is ready to occur, they will need to start discussions now. ■

Source: Adapted from materials produced by the Pew Initiative on Food and Biotechnology, including September 2004 conference papers on biotech bugs.