Transgenic Crops

Biotechnology has already created plants that withstand pests and fruits that resist spoilage. Recent advances confirm its environmental soundness and commercial viability

by Charles S. Gasser and Robert T. Fraley

Modification of crop plants to improve their suitability for cultivation has persisted for at least 10,000 years. Early farmers produced better crops simply by saving the seeds of desirable plants. During the past century, plant breeding has become more rigorous in its approach. Significant improvements in crops have resulted from the successful crossbreeding of different individuals of the same species. More recently, researchers have made advances in crossing sexually incompatible species of the same family. Now there exists a promising method of developing superior plants: genetic engineering. By using recombinant DNA techniques, biologists can direct the movement of specific and useful segments of genetic material between unrelated organisms.

That approach can add a significant degree of diversity to the total repertoire of traits from which the plant breeder can choose. In the laboratory, plants can now be made to withstand insects, viruses and herbicides. Fruits can be made to resist spoilage, and grains may become more nutritious and economical.

Biologists created the first transgenic plants less than 10 years ago. Since then, researchers have applied genetic engineering to more than 50 plant species. The technique has helped investigators gain critical insights into the fundamental processes that govern the development of plants, and the first commercial introductions of such genetically modified plants are now only a few years away.

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Although genetic engineering is more complex than traditional plant-breeding practices, it is just as safe. In both methods, new DNA enters the plant's genome and is stably maintained and expressed. A recent National Academy of Sciences report concluded that "crops modified by molecular and cellular methods should pose risks no different from those modified by classical genetic methods for similar traits." This past February the White House stated that genetically engineered products should not be subject to additional federal regulations, because they do not pose any unreasonable risk.

In this article, we shall describe the methods used at present to engineer plants genetically. We shall also outline the rationale of and progress in the current applications.

The first practical—and still the most widely used—system for genetic engineering of plants relies on an innate ability of the plant pathogen *Agrobacterium tumefaciens.* This bacterium can transfer a portion of its DNA into plant cells. It does so by introducing a set of genes into one or more of its own DNA fragments. These fragments, called transferred DNA (T-DNA), then integrate into chromosomes of infected plant cells and induce the cells to produce elevated levels of plant hormones. These hormones cause the plant to form novel structures, such as tumors or prolific root masses, that provide a suitable environment and nutrient source for the *Agrobacterium* strain. This bacterial infection is called crown gall disease.

For the bacterium to be an effective vehicle for DNA transfer, its disease-causing genes had to be removed. This alteration is known as disarming. Researchers at the Monsanto Company and Washington University and groups directed by Jozef Schell of the Max Planck Institute for Plant Breeding in Cologne and by Marc van Montagu of the State University of Ghent in Belgium first accomplished the task in 1983. They relied on traditional DNA recombination to delete the genes that cause tumors. Disarming thus eliminates the bacterium's ability to cause disease but leaves the mechanism of DNA transfer intact [see "A Vector for Introducing New Genes into Plants," by Mary-Dell Chilton; SCIENTIFIC AMERICAN, June 1983].

The first engineered gene, constructed with *Agrobacterium* in the early 1980s by groups at the Max Planck Institute in Cologne and at Monsanto, made plant cells resistant to the antibiotic kanamycin, a compound that inhibits plant growth. The engineering of kanamycin resistance represented a breakthrough for two reasons. First, it showed that foreign genes and proteins could be expressed in plants. Second, it demonstrated that kanamycin resistance is useful as a "marker." Because only a small number of cells take up, integrate and express introduced DNA, marker genes help investigators to identify those cells into which genes have successfully been introduced.

Because plant cells are totipotent—that is, the undifferentiated cells can generate a whole organism—complete, reproductively competent plants can emerge from the transformed cells. Most methods today rely on the cells of explants, or small pieces of plant, for genetic engineering. Our colleague Robert B. Horsch of Monsanto popularized the use of a common paper hole punch to cut disks from leaves for *Agrobacterium*-mediated techniques. (He used to carry a punch in his coat pocket, always ready to give an impromptu demonstration of the leaf-disk transformation method.) *Agrobacterium*-mediated gene transfer is now routinely used in hundreds of industrial and academic laboratories around the world. At Monsanto alone, more than 45,000 independent transgenic plant lines have been produced in this way.

Although the method is simple and precise, many plant species, including such critical grain crops as rice, corn and wheat, are not natural hosts for *Agrobacterium* and so are not readily transformed by the method. As a result, extensive efforts have been mounted to develop alternative systems.

One of the first was introducing free DNA into plant protoplasts. Protoplasts, plant cells that have had their cell walls removed by enzymes, must be used because the pores of cell walls are too small to allow the easy passage of DNA. The only barrier in protoplasts is the plasma membrane. Polyethylene glycol, a thick organic polymer, can penetrate the plasma membrane to transport DNA. It is the most commonly used chemical delivery agent. Electroporation can also carry DNA across the plasma membrane. In this process, short, high-voltage pulses briefly produce pores in the protoplast membrane. The DNA molecules can enter through these spaces.

Because these procedures do not rely on any special biological interaction, they are, in principle, general methods of transforming cells. But the regeneration of plants from isolated protoplasts has proved problematic in many species, especially the critical cereal grains. Corn and wheat respond very poorly, usually yielding infertile plants.

As a result, investigators have been searching for methods that introduce DNA into intact plant cells, those that still have their walls. A fairly obvious way is simply injecting the DNA. But microinjection has not been effective for several reasons. The fine needle tips break easily and clog frequently. Transforming cells one at a time is tedious, difficult work that would be inappropriate to a commercial operation. Furthermore, once DNA enters a cell, its incorporation into the genome of the recipient is by no means a certainty. A technician might have to inject DNA

GENETICALLY ENGINEERED RESISTANCE to the Colorado potato beetle *(Leptinotarsa decemlineata)* is shown in this false-color, infrared aerial image of test beds planted in a field recently irrigated by a center-pivot system at Hermiston, Ore. The beetles defoliated fields of ordinary potato plants, leaving behind wet ground (*green*), but avoided plants that were able to produce their own insecticide (*red*). The white patches are wheat plants kept dry for an unrelated experiment.

into at least 10,000 cells just to ensure that one of them will take up the new gene.

To increase the efficiency of gene delivery, John C. Sanford of Cornell University envisioned a way to bombard many plant cells with genetic material. He surmised that small metal particles, about one or two microns in diameter, could first be coated with DNA. Sufficiently accelerated, the particles could penetrate the walls of intact cells and thus deliver the DNA. Because small holes in cell walls and membranes rapidly close by themselves, the punctures are temporary and do not irreversibly compromise the integrity of the cells. Although the particles remain in the cytoplasm, they are too small to interfere with any cellular functions.

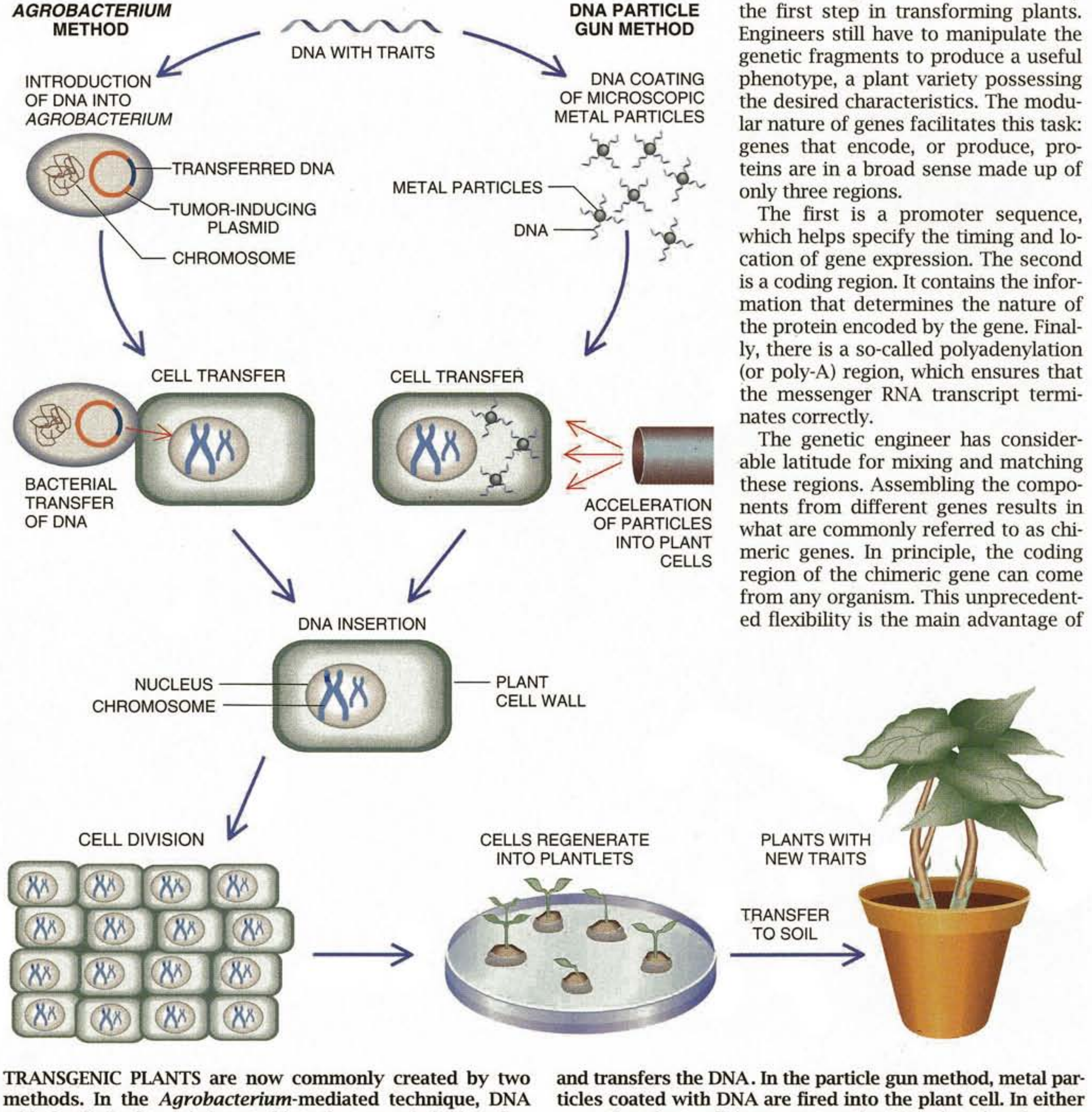
In 1987 Sanford and his co-worker Theodore M. Klein constructed a practical device that used tungsten particles to bombard plant cells. Their DNA particle gun, as it is called, uses a .22-caliber blank cartridge as the motive force. Researchers at Agracetus in Middleton, Wis., have developed a similar gun using gold particles propelled by the vaporization of a water droplet.

Both these particle guns have produced transgenic plants. Last year a group at DeKalb Plant Genetics in Groton, Conn., and a collaboration between Charles L. Armstrong of Monsanto and Michael E. Fromm, then at the U.S. Department of Agriculture in Albany, Calif., independently developed efficient, consistently functioning particle gun systems for the transformation of corn. Even more recently, we have collaborated with Indra Vasil's laboratory at the University of Florida in Gainesville to transform wheat plants.

Introducing DNA into cells is only the first step in transforming plants. Engineers still have to manipulate the genetic fragments to produce a useful phenotype, a plant variety possessing the desired characteristics. The modular nature of genes facilitates this task: genes that encode, or produce, proteins are in a broad sense made up of only three regions.

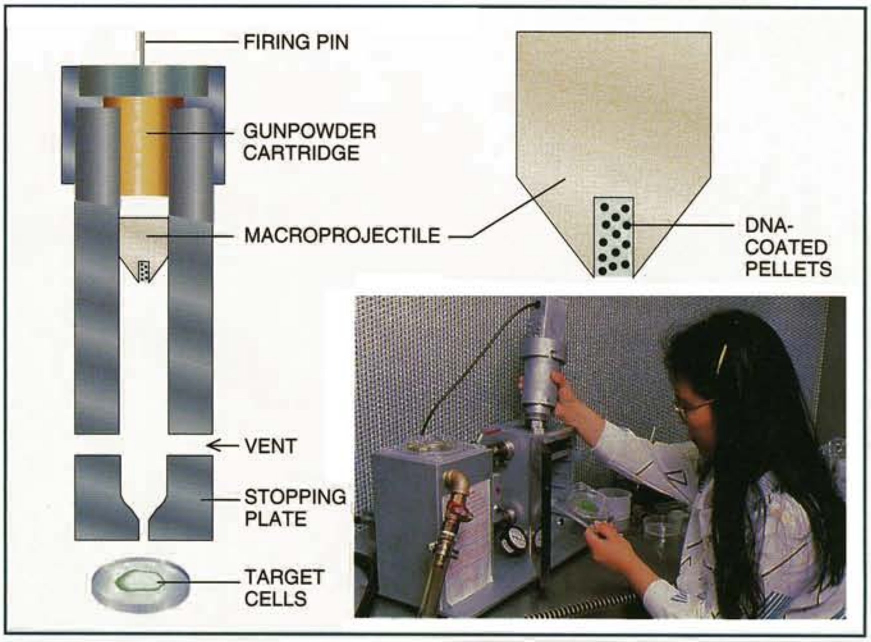
The first is a promoter sequence, which helps specify the timing and location of gene expression. The second is a coding region. It contains the information that determines the nature of the protein encoded by the gene. Finally, there is a so-called polyadenylation (or poly-A) region, which ensures that the messenger RNA transcript terminates correctly.

The genetic engineer has considerable latitude for mixing and matching these regions. Assembling the components from different genes results in what are commonly referred to as chimeric genes. In principle, the coding region of the chimeric gene can come from any organism. This unprecedented flexibility is the main advantage of



TRANSGENIC PLANTS are now commonly created by two methods. In the *Agrobacterium*-mediated technique, DNA with the desired trait is inserted into the tumor-inducing plasmid of the bacterium. The bacterium infects the plant cell and transfers the DNA. In the particle gun method, metal particles coated with DNA are fired into the plant cell. In either case, the plant cell incorporates the DNA into its chromosome and then divides and regenerates into full plants.

genetic engineering over more traditional methods, which can transfer genes only between closely related species. Furthermore, by choosing various promoters, researchers can target gene expression to specific organs such as leaves, roots, seeds and tubers and, in many cases, to specific cell types within these complex tissues.



DNA PARTICLE GUN developed by John C. Sanford of Cornell University fires tungsten pellets coated with DNA into plant cells. The pellets are held by a plastic macroprojectile, which is accelerated by a gunpowder charge. The plate stops the macroprojectile; momentum sends the pellets into the target. The vents allow air in front of the projectile to escape. In the photograph, a technician readying the device holds the "gun barrel" in her right hand; the cells to be transformed are in her left.

One of the most promising traits gene transfer offers is resistance to diseases. Exciting results have been achieved in creating plants resistant to viruses, an important matter because currently no direct way to treat virus-infected crops exists. Most infections reduce crop yield, but occasionally some prove catastrophic. Good farming practices, such as rotating crops and removing weeds and crop litter, can contain viruses, but only partially. Insecticides are sometimes used to control the pests responsible for transmitting the virus.

Genetic work on virus resistance builds on previous basic research in plant biology. It had long been observed that infection of a plant with a mild strain of a virus protected it from subsequent infection of a more virulent strain. Apparently, the replication of the mild virus strain interferes with a virulent strain's ability to infect. Investigators have applied "cross-protection" to shield greenhouse-grown tomatoes against contagion by intentionally infecting them.

Roger N. Beachy and his co-workers at Washington University reasoned that a single component of the virus might be responsible for the protection. Collaborating with Stephen Rogers of Monsanto and one of us (Fraley), the investigators constructed a vector to introduce and express in tobacco and tomato plants the coat protein of the tobacco mosaic virus (TMV). Plants so modified were then inoculated with a heavy concentration of the virus. The plants were found to be strongly resistant to infection, thus confirming Beachy's hypothesis of viral protection.

Subsequent experiments have shown that the expression of the TMV coat protein confers resistance only to strains of TMV and a few other closely related viruses. Still, the mechanism appears to be generally applicable; expression of the coat protein gene of almost any plant virus, at a sufficiently high level, protects against infection by that virus. Workers have now engineered effective tolerance to more than a dozen different plant viruses in a broad range of crop species.

Resistance to insect predation is another important goal for genetic engineering, especially in cotton, potato and corn plants. During the past three decades, gardeners and farmers have relied on the bacterium *Bacillus thuringiensis* (*Bt*), which produces an insecticidal protein. Most commonly used preparations of *Bt* are highly specific to the caterpillar larvae of lepidopteran insects—moths and butterflies—which are major pests. The *Bt* proteins bind to specific receptors located on the gut membranes of the target insects. The binding interferes with ion transport in the epithelial cells of the gut, thus disrupting the insect's ability to feed. These natural insecticides have no toxicity to mammals or even to any other species of insects.

The usefulness of the *Bt*-based insecticides is often limited by the ease with which they are washed from plants. Furthermore, their effectiveness in the field lasts only briefly. In the mid-1980s genetic engineers at several companies, such as Plant Genetic Systems in Ghent, Belgium, Agrigenetics in Middleton, Wis., Agracetus and Monsanto, succeeded in isolating from the bacterium genes for the insecticidal proteins. They used the particle gun and *A. tumefaciens* to insert the genes into tomato, potato and cotton plants. At first, the genes expressed poorly; the *Bt* proteins the plant produced killed only the most sensitive laboratory insects.

Monsanto scientists David A. Fischhoff and Frederick J. Perlak made improvements. They redesigned the original bacterial gene to mimic more closely the plant DNA sequences. The changes dramatically enhanced insect control. Two years of field testing have confirmed that the presence of these *Bt* genes within cotton plants effectively controlled all major caterpillar pests, including the bollworm. These genetically engineered plants should reduce the use of insecticides on cotton by about 40 to 60 percent.

Scientists have screened extensively for naturally occurring *B. thuringiensis* strains that are effective on insects other than caterpillars. One such strain has led to the redesign of a gene that is effective against the Colorado potato beetle. In the summer of 1991, Russet Burbank potato plants expressing a beetle-control gene were tested at several sites from Maine to Oregon. Researchers found the potato plants to be essentially immune to beetle damage.

Bt may continue to offer additional genes for the control of plant pests. Scientists at Mycogen Corporation in San Diego have now discovered *Bt* genes active against plant parasitic nematodes, and *Bt* genes active against mosquitoes have been identified. Some researchers are trying to produce the mosquitocidal protein in algae as a means to control malaria.

The target specificity of the *Bt* protein and its localization within the tissues of the plant ensure that the protein is active only against attacking insects. In contrast to topical insecticides, proteins in the plant obviously cannot be washed off. Extensive toxicological testing of *Bt* proteins and experience gained from more than 30 years of using *Bt*-based products confirm their safety. In fact, many researchers refer to *Bt* as the world's safest insecticide. Furthermore, the *Bt* protein, which makes up less than 0.1 percent of the total protein in the modified plants, breaks down in exactly the same fashion as any other protein—both in the soil and the digestive tract.

Besides the threat from viruses and insects, crops face a challenge from weeds. Weeds that compete for moisture, nutrients and sunlight can reduce a field's potential yield by 70 percent. Moreover, weed material in the harvest significantly reduces the value of the crop, and weeds serve as a habitat for pests.

In most cases, a combination of herbicide and careful cultivation effectively controls weeds. But because a herbicide has a limited spectrum of activity, affecting only a small portion of the weeds, several kinds of chemicals are often used during the growing season.

Genetic engineering may offer a partial alternative to such weed control. The strategy is to create plants that can tolerate exposure to a single, broad-spectrum, environmentally safe herbicide. In contrast to views expressed by some critics of genetic engineering, the use of herbicide-tolerant plants will actually reduce the overall amount of herbicide applied.

There are two general approaches to engineering herbicide tolerance. Researchers at Monsanto and at Calgene in Davis, Calif., have been working to enable plants to tolerate glyphosate, the active ingredient of a herbicide called Roundup. Roundup is a broad-spectrum compound that can control broadleaf and grassy weeds. The compound kills plants by inhibiting the action of EPSP synthase. This enzyme is necessary for the production of the aromatic amino acids that a plant needs if it is to grow.

Genetic engineers are especially interested in Roundup because it is one of the most environmentally attractive herbicides. It does not affect animals, because animals do not have an aromatic amino acid pathway. Furthermore, it degrades rapidly in the environment into harmless, natural compounds.

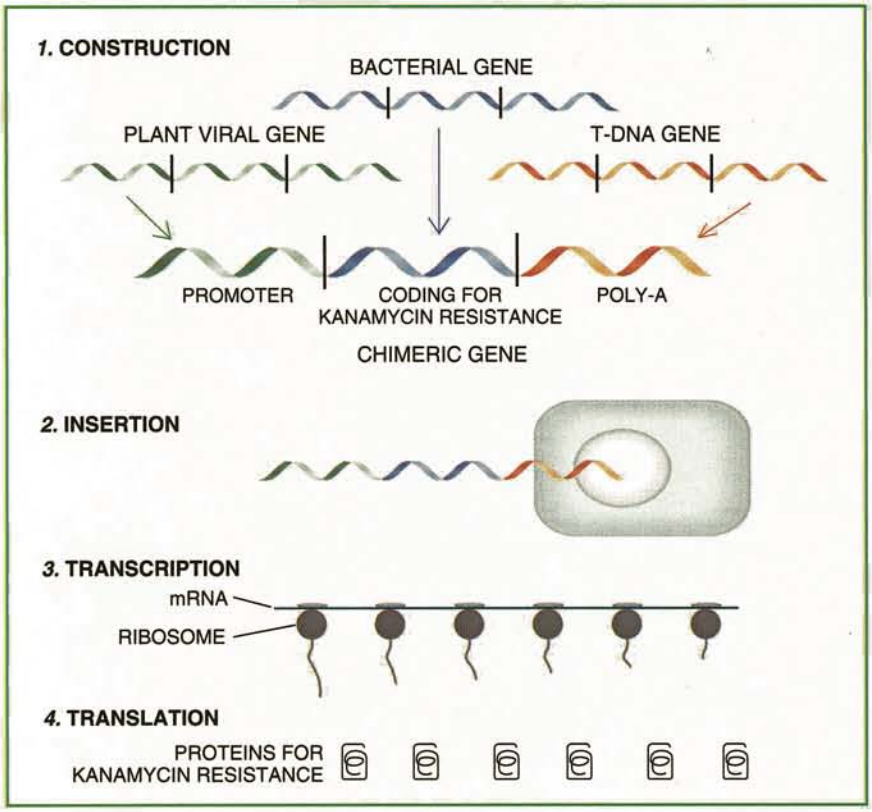
The first step in developing Roundup tolerance took place in 1983, when groups headed by Luca Comai and David M. Stalker of Calgene and Rogers and Ganesh Kishore of Monsanto isolated the genes for EPSP synthase from bacteria and plants. They also identified variants of the genes that produce proteins that have reduced sensitivity to Roundup. Later, investigators were able to construct genes that produced higher amounts of these proteins in plants. The genes were subsequently introduced into tomato, soybean, cotton, oilseed rape and other crops. As demonstrated by field tests performed during the past three years in the U.S., Canada and Europe, the crops were able to tolerate treatment with Roundup at levels that effectively controlled weeds. Researchers at Du Pont have used a technically similar approach to engineer plants that can tolerate certain kinds of sulfonylurea herbicides.

Scientists at Plant Genetic Systems and at the German company Hoechst took another approach to herbicide tolerance. From the microbe *Streptomyces hygroscopicus,* they isolated a gene for an enzyme that inactivates a herbicide called Basta, which affects the glutamine synthase pathway in weeds and thus interferes with their growth. But crop plants that have the gene inactivate Basta before damage can occur. Field tests performed on the Basta-tolerant plants demonstrate the effectiveness of the protection.

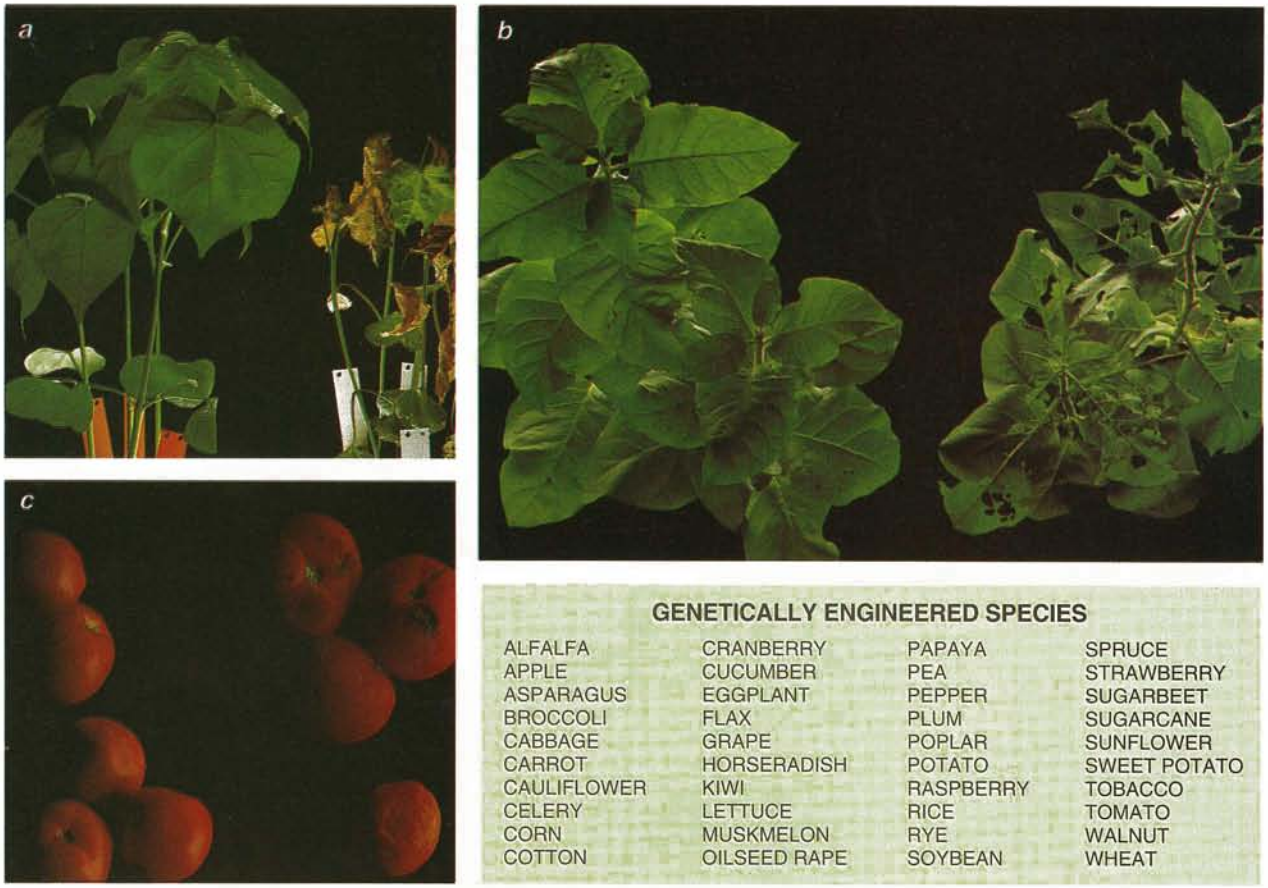
Engineered herbicide tolerance offers the farmer an alternative that is lower in cost and more effective than conventional weed-management measures. Careful selection of broad-spectrum herbicides should lead to an overall decrease in the use of weed-control chemicals and should enable farmers to replace existing herbicides with environmentally more attractive products.

Additional advances in the simplicity and breadth of genetic engineering techniques and increasing knowledge of plant biology promise to extend greatly the beneficial changes that gene transfer can confer. For example, researchers have already identified and isolated several genes that play a role in the biosynthesis of ethylene, the signal molecule that triggers the ripening of fruits. Delayed spoilage would allow harvesting at a later stage than is currently practical, which may improve the flavor and even the nutritional value.

To increase the shelf life of fruit, re-



CHIMERIC GENES can be constructed from the genes of different organisms. Here the chimeric gene for kanamycin resistance is assembled from diverse sources: the promoter region of a plant virus, the coding region of an *E. coli* bacterium and the poly-A site from the transferred DNA (T-DNA) of *Agrobacterium* (*1*). After the chimeric gene is inserted into a plant cell (*2*), it is transcribed into messenger RNA (mRNA) (*3*). The ribosomes translate the mRNA to produce the proteins (*4*).



GENETICALLY ENGINEERED SPECIES

ALFALFA
APPLE
ASPARAGUS
BROCCOLI
CABBAGE
CARROT
CAULIFLOWER
CELERY
CORN
COTTON
CRANBERRY
CUCUMBER
EGGPLANT
FLAX
GRAPE
HORSERADISH
KIWI
LETTUCE
MUSKMELON
OILSEED RAPE
PAPAYA
PEA
PEPPER
PLUM
POPLAR
POTATO
RASPBERRY
RICE
RYE
SOYBEAN
SPRUCE
STRAWBERRY
SUGARBEET
SUGARCANE
SUNFLOWER
SWEET POTATO
TOBACCO
TOMATO
WALNUT
WHEAT

GENETICALLY TRANSFORMED CROPS, shown to the left of their ordinary counterparts in each photograph, include herbicide-tolerant cotton plants (*a*), insect-resistant tobacco plants (*b*) and tomato plants whose fruits resist spoilage (*c*). The list identifies familiar plant life in which genetic engineering has successfully been demonstrated.

searchers developed two genetic methods. The first is inserting so-called antisense versions of the ripening genes. Antisense molecules bind with specific messenger RNA to turn off the genes. Athanasios Theologis of the USDA in Albany, Calif., and Don Grierson of the University of Nottingham have shown that fruits of tomato plants with the antisense genes resist softening. In a different approach, Monsanto scientists Kishore and Harry Klee have introduced a gene into tomato plants that induces them to manufacture an enzyme. This enzyme degrades the precursor compounds that form ethylene, thus retarding spoilage.

Genetic engineers may also be able to fashion healthier foods: genes for proteins that have superior nutritional properties have been isolated. It should be possible to insert these genes into crops. Plants could also be tailored to produce specialty chemicals such as starches, industrial oils, enzymes and even pharmaceuticals. Preliminary trials are now under way.

More than 400 field tests of engineered plants have now been conducted in the U.S. and Europe. The tests confirm the inherent safety and commercial validity of these approaches, and crops containing these traits should be available to farmers during the mid-1990s. Still, there are some limitations. In practical terms, genetic engineers can only modify traits expressed by no more than three to five genes. Furthermore, some crops do not respond to current gene-transfer methods, and isolating useful genes is sometimes difficult.

Yet to many in plant biotechnology, these challenges seem less likely to delay commercialization than are nontechnical issues. Genetically modified crops are being developed at a time when both public and political support for agricultural research is in general tepid. Concerns about food safety, the environmental impact of agriculture and a rapidly changing farm infrastructure have combined with a lack of understanding of new technologies to overshadow the long-term need for economical, high-quality food products. World food production will have to increase threefold during the next 40 years to meet the needs of an estimated nine billion people. Biotechnology is one of the few new solutions to this problem.

Another important advantage of the genetic engineering of plants is that it provides the very latest technology to farmers in a very traditional package—the seed. Even the most impoverished nations will thus have access to the benefits without the need for high-technology supplies or costly materials. Although not a panacea, biotechnology promises to become an important component of agriculture around the world.

FURTHER READING

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SOWING A GENE REVOLUTION

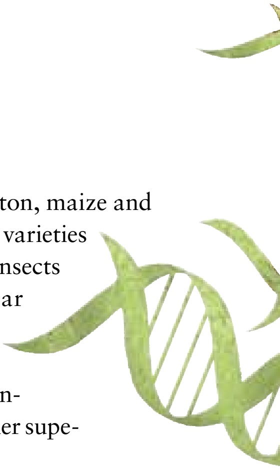
A new green revolution based on genetically modified crops can help reduce poverty and hunger—but only if formidable institutional challenges are met

By Terri Raney and Prabhu Pingali

The number of hungry people in the world remains stubbornly high. In 1960 roughly one billion people were undernourished; tonight about 800 million still will go to bed hungry. Yet the progress in filling empty bellies has been much more substantial than those two numbers might suggest, because today around 5.6 billion people are fed adequately, compared with only two billion half a century ago.

Modern agricultural technology has been the key to these dramatic gains. The development and distribution of high-yield seeds and the inputs (fertilizers and irrigation) to make them grow to their full potential drove the green revolution of the 20th century. Conventional methods of selective breeding and the crossing of different varieties produced hybrids with desirable characteristics that increased farm productivity and incomes and brought down food prices.

Now we could be witnessing a nascent "gene revolution." In recent decades, researchers have developed and honed techniques to transplant individual genes from one organism to another, creating cultivars with valuable new traits. For example, a gene from the soil bacterium *Bacillus thuringiensis,* transferred to cotton, maize and other plants, leads to so-called Bt varieties that have an innate resistance to insects such as borer beetles. In similar fashion, scientists have invented herbicide-tolerant soybeans, more nutritious, beta-carotene-enriched Golden Rice and some other superior crops.



Transgenic crops are spreading faster than any other agricultural technology in history, despite continuing controversy about potential risks such as gene flow (the escape of inserted transgenes into related crops or wild plants), the emergence of resistant pests, and fears that eating genetically modified foods might affect the health of consumers. The U.S. and Canada grow the bulk of transgenic crops—60 percent by area cultivated—but developing countries accounted for 38 percent in 2006, almost all of that in Argentina, Brazil, India and China.

If the promise of genetically modified crops to reduce hunger significantly is to reach full fruition, however, the crops must prove their economic value to poor farmers, who will grow them only if they can increase their profits by do-

JON KRAUSE

KEY CONCEPTS

- Genetically modified crops can increase the profits of farmers in developing nations and reduce food prices for poor consumers, but they are not a panacea.
- Unlike the green revolution of the 20th century, in which public research institutes developed technologies and freely disseminated them around the world, today's "gene revolution" is led by multinational corporations.
- Reaping the full potential of biotechnology in the developing world will depend as much on institutional factors (such as intellectual-property rights and environmental and food safety regulations) as on the development of transgenic crops suited to the local conditions in each country.

—The Editors

ing so. Recent peer-reviewed studies have shown that farmers in developing countries have indeed benefited by growing transgenic crops. These farmers saw increased yields and lowered expenditures on pesticides that more than compensated for the higher costs of the transgenic seeds. In some cases, smaller farms gained proportionally more profit than larger farms did, contradicting the widely held perception that transgenic crops help only large farms, which can take advantage of economies of scale. The data also run contrary to the fear that multinational biotechnology firms are capturing all of the economic value created by transgenic crops. Rather consumers and farmers share the benefits with the firms.

The studies revealed, however, that profitability varied greatly from country to country or even between regions within a nation. At least as important as the performance of the technology are institutional factors—the agricultural research capacity of a nation, the functioning of its agricultural input markets (such as distribution of seeds) and the overall policy circumstances, including regulations relating to the environment, food safety, trade and intellectual-property rights. Only if formidable institutional challenges are met can transgenic crops achieve their full potential to improve the livelihoods of farmers in the developing world.

In addition to increasing food production and reducing poverty, transgenic crops could alleviate some environmental problems caused by intensive agriculture. For instance, farmers who grow Bt crops can reduce their use of chemical pesticides that do harm to nontarget species such as bees. Herbicide-tolerant crops let them decrease their use of the most toxic compounds, albeit with an overall increase in lower-toxicity herbicides. Herbicide-tolerant crops are also as-

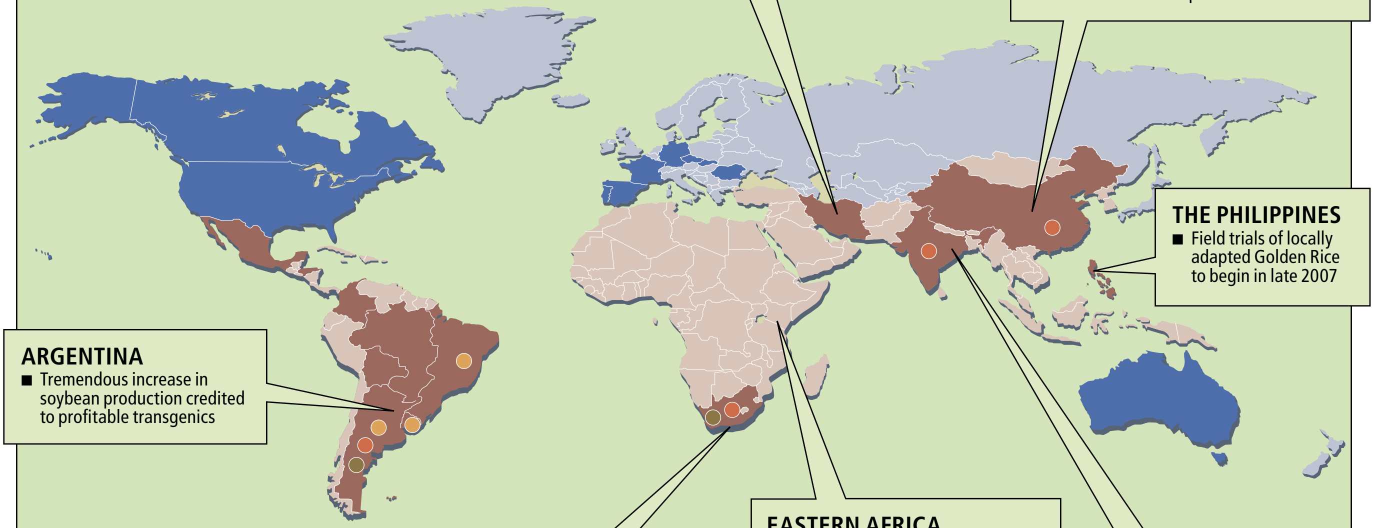
[THE STATUS QUO]

THE GENETICALLY MODIFIED WORLD

Twenty-two countries, both industrial (*blue*) and developing (*brown*), grow genetically modified crops. The map below presents a selection of facts about the development and commercial production of transgenic crops in developing nations; much more is under way.

MAJOR DEVELOPING-WORLD PLANTINGS OF TRANSGENIC CROPS

● **Soybean:** Argentina, Brazil, Paraguay
● **Maize:** Argentina, South Africa
● **Cotton:** China, India, Argentina, South Africa



IRAN

- Only country to approve Bt (insect-resistant) rice for commercial cultivation

CHINA

- On the brink of approving Bt rice for commercial cultivation
- Only developing country where farmers are cultivating transgenic crops (insect-resistant cotton) developed independently of the international private sector

THE PHILIPPINES

- Field trials of locally adapted Golden Rice to begin in late 2007

ARGENTINA

- Tremendous increase in soybean production credited to profitable transgenics

AFRICA IN GENERAL

- Staple crops with no transgenic varieties yet available: sorghum, chickpea, cassava, pearl millet, pigeon pea and groundnut

SOUTH AFRICA

- First developing country to plant a transgenic staple food (2001, Bt white maize)
- University researchers developed maize resistant to maize streak virus
- Preliminary work is under way on developing maize tolerant of drought based on genes from plants indigenous to Africa

EASTERN AFRICA

- Maize streak virus is endemic

BANGLADESH, CHINA, INDIA, INDONESIA, THE PHILIPPINES, SOUTH AFRICA, VIETNAM

- Research institutes are working with Syngenta to develop locally adapted varieties of Golden Rice

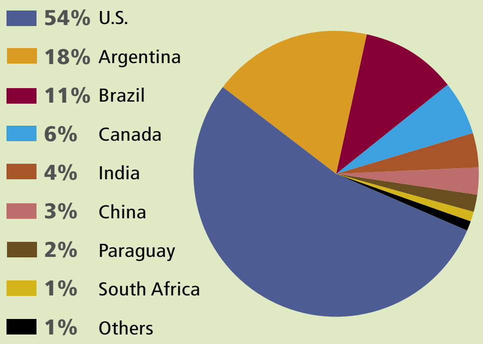
INDIA

- Indian researchers have developed transgenic eggplant, maize, pigeon pea, mustard, tomato, rice, okra, cabbage and cauliflower. Initial small-scale field trials are under way

Most transgenic crop plantings are in the U.S. (*below left*), but since 2000, plantings have increased faster in developing nations than in industrial ones (*below middle*). A small number of crops and kinds of modification account for almost all the production (*right*).

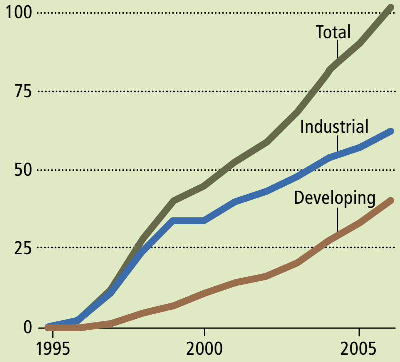
THE BIG GROWERS

Transgenic crop area by country (2006)



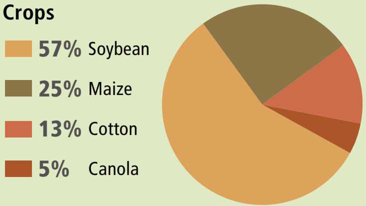
RAPID INCREASES IN TRANSGENICS

Millions of hectares planted



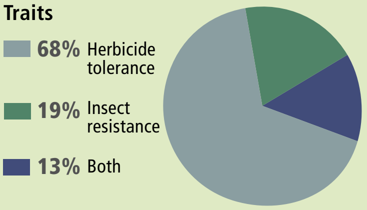
KINDS OF PLANTINGS (2006)

Crops



Other biotech crops: rice, squash, papaya and alfalfa (less than 1%)

Traits



DANIELA NAOMI MOLNAR; SOURCE: *GLOBAL STATUS OF COMMERCIALIZED BIOTECH/GM CROPS*; ISAAA BRIEFS 35; 2006 (*pie charts and graph*); GEORGE RETSECK (*map*)

sociated with the adoption of low- or no-till cropping practices, which reduce soil erosion and the disruption of soil structure and microbial communities. Thus, transgenic crops could help bring about a "doubly green revolution."

Technology Is Vital

It is unfashionable to focus on agriculture and technology as a means to address poverty and hunger. Critics argue—correctly—that the world produces enough food to provide everyone with an adequate diet and that what is required is more equitable access for the poor. They extrapolate from these sensible observations to the mistaken conclusion that technological advances are unimportant or even counterproductive in the fight against poverty and hunger. The evidence proves them wrong. Technological innovation in agriculture is necessary (though not sufficient) to create sustainable economic growth and alleviate poverty in developing countries.

Agriculture is the fundamental driver of economic growth in agrarian societies. The technologies that fueled the green revolution brought enormous benefits to poor people. Modern varieties of wheat, rice and maize became available to millions of poor farmers in the developing world, first in Asia and Latin America and later (though to a lesser degree) in Africa. By raising agricultural productivity, the green revolution lifted farm incomes and reduced food prices, making food more affordable for the poor. This virtuous cycle of rising productivity, improving living standards and sustainable economic growth has lifted millions of people out of poverty.

The gene revolution, however, differs in significant ways that raise fundamental questions about whether poor farmers in developing countries will have access to appropriate transgenic crops on favorable terms. Multinational corporations conduct most biotech research—in contrast with the public-sector researchers at national and international levels who were behind the green revolution. And whereas those public institutions freely disseminated and shared the agricultural technologies of the last revolution, multinationals hold their inventions under exclusive patents and distribute them commercially. This shift in the source of the technology affects the kind of research that is being done, the type of products being created and their eventual accessibility for poor farmers.

China is the only developing country where farmers are cultivating transgenic crops developed independently of the international private sector. Some developing countries—notably India, Brazil and South Africa—are conducting field trials on independently developed transgenic crops, but they have not been released for commercial production. Few others have the technical capacity for independent transgenic crop research and development. The Consultative Group on International Agricultural Research (CGIAR) system, a partnership of countries, organizations and private foundations, supports the work of some international research centers that are collaborating with national research systems and the private sector on transgenic crops for developing countries, but these programs are small and poorly funded.

Private-sector biotechnology research is naturally focused on highly profitable technologies suitable for farms in the temperate-zone environments of North America and Europe. Some farmers in developing countries (primarily in temperate zones in South America, South Africa and China) have taken advantage of "spillover" benefits from that work, but many others till in conditions, such as drought-prone regions of the tropics, that require dedicated solutions.

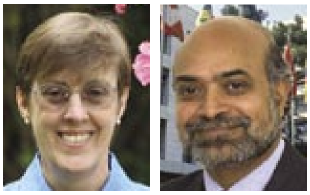
Very few major public- or private-sector programs are targeting crops and animals that the poor rely on or the particular problems that they face. Traits of special interest to the developing world include nutritional enhancement and resistance to production stresses such as drought, salinity, disease and pests. Crops that provide the majority of their food supply and livelihoods—rice and wheat—are being neglected, as are a variety of "orphan crops" (such as sorghum, pearl millet, pigeon pea, chickpea and groundnut). Those are staple foods in some regions and have also been largely passed over by conventional agricultural research programs.

Research for the Poor

Nevertheless, although their resources are dwarfed by those of programs aimed at more lucrative markets, researchers in many countries are working on transgenic approaches to the issues facing farmers in developing countries. Joel Cohen of the International Food Policy Research Institute surveyed the public research pipelines in 15 developing countries in 2003 and found 201 genetic transformations for 45 different crops, including cereals, vegetables,

For more about the green revolution, including discussion of criticisms about it, log on to: **www.SciAm.com/ontheweb**

[THE AUTHORS]



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The views expressed in this article are those of the authors and do not necessarily reflect the views of the FAO.

COURTESY OF TERRI RANEY (*Raney*); MELVIN DENISE (*Pingali*)

roots and tubers, oil crops, sugar and cotton.

By far the most important food crop in the developing world is rice. Researchers are developing several transgenic rice varieties with farmers and consumers in poor countries in mind, including insect-resistant Bt rice and Golden Rice.

Field trials in China suggest that Bt rice can help small farmers in many ways. By conferring resistance against some major crop pests, Bt rice reduces the need for chemical pesticides. Because farmers achieve better pest control, they gain higher effective yields at a lower cost. They also suffer less exposure to chemicals. (Small farmers in China typically use backpack sprayers with little or no protective gear and thus suffer high rates of insecticide poisoning.) The reduction in the use of broad-spectrum insecticides that kill many types of insects besides the target pests is also likely to be an environmental boon.

So far Iran is the only county that has approved Bt rice for commercial cultivation (on about 5,000 hectares in 2006). China is on the brink of permitting commercial cultivation of Bt rice but has held back, reportedly because of concerns about the possible loss of exports to nations that do not accept transgenic crops.

Golden Rice is perhaps the best-known transgenic crop developed specifically to meet the needs of undernourished people. It is designed to combat vitamin A deficiency, which claims 3,000 lives every day and causes half a million cases of infant blindness a year. For many of these people, up to 80 percent of daily calories consumed are from polished white rice, which contains no beta-carotene (the human body converts beta-carotene to vitamin A).

The first generation of Golden Rice included a gene from daffodils and another from a common soil bacterium, *Erwinia uredovora,* that together produce beta-carotene in the grain. Developed in 2000 by Ingo Potrykus of the Swiss Federal Institute of Technology in Zurich, Peter Beyer of the University of Freiburg in Germany, and a network of academic and humanitarian organizations, the original Golden Rice was sharply disparaged as a technological solution to a problem caused by poverty and social exclusion. Critics also argued that Golden Rice would encourage people to rely on a single food rather than diversifying their diets. They claimed that the money spent on developing Golden Rice would have been better devoted to enabling people to eat a balanced diet of grains, fruits, vegetables and proteins. Of course, many of the world's poorest cannot afford such meals, and these are the very people Golden Rice is intended to reach.

Detractors also noted that a normal serving of Golden Rice contained only a small fraction of the recommended daily allowance (RDA) of beta-carotene. Scientists at Syngenta therefore developed Golden Rice 2 by replacing the daf-

[GENES FOR AFRICA]

A CHAMPION FOR BIOTECH

Jennifer Thomson of the University of Cape Town in South Africa staunchly advocates transgenics for their potential to help alleviate hunger and poverty in Africa. In addition to leading a group developing varieties of transgenic maize crafted for African conditions, she has helped draft South Africa's regulations concerning genetically modified organisms and serves as chair of the Nairobi-based African Agricultural Technology Foundation (AATF).

Thomson's research group has spent 12 years creating maize resistant to the maize streak virus, which is endemic in eastern Africa. The scientists fashioned laboratory lines of resistant maize and conducted successful greenhouse trials. Laboratory lines are easier to genetically engineer than typical plants, but their other characteristics make them of no use for agriculture. Thomson's group has therefore licensed its virus-resistance technology to Pannar Seed International in KwaZulu-Natal, which is "doing the lion's share of the commercialization," she says. "They have transferred our resistance into commercially viable lines, and they are ecstatic. We are working on our application for field trials."

Thomson's group also seeks to produce a drought-tolerant maize using genes from the "resurrection plant," *Xerophyta viscosa,* which can recover from 95 percent dehydration. That research is at a very early stage, and the scientists are still determining which genes to transfer. "We're testing [genes] singly and we're going to be testing them in combination. It's going to be a long-term project," Thomson says.

She says it is "absolutely" important for developing nations to conduct their own biotechnology research, including adapting technologies invented by multinationals. "Multinationals aren't interested in the crops we are interested in in Africa," she explains. "For instance, in West Africa we are interested in cowpeas. What multinational is interested in cowpeas? The AATF transfers intellectual property in biotech agriculture from multinationals to Africa. We've recently done a very successful [transfer] for insect-resistant cowpeas." Through the AATF, multinationals "are being incredibly helpful" in Africa, she says.

Yet for her own research, she has "resolutely refused money from multinationals, to keep [the technology] in the public domain." For many years the maize streak virus project has been funded largely by the Claude Leon Foundation, "a philanthropic foundation that saw that virus-resistant maize would help Africans to survive." More recently Pannar has helped considerably, both financially and in kind (such as by testing the plants developed by Thomson's group). Says Thomson, "I don't want anybody to cause my maize to be more expensive." —***Graham P. Collins***

"RESURRECTION PLANT" can completely recover (*top*) from up to 95 percent dehydration (*bottom*).

COURTESY OF JENNIFER THOMSON

fodil gene with an equivalent gene from maize. This modification increased the amount of beta-carotene by about 20-fold. Around 140 grams of the rice could provide a child's RDA for beta-carotene. In households that depend on rice for sustenance, a child's portion is typically about 60 grams, and he or she may eat several portions during the day.

Syngenta, a member of the Humanitarian Golden Rice Network, obtained free licenses from 32 companies and academic institutions for the humanitarian use of the patents needed to make Golden Rice. The company is working with public research institutions in Bangladesh, China, India, Indonesia, the Philippines, South Africa and Vietnam to develop locally adapted varieties of Golden Rice. Once the researchers have tested their varieties and obtained approval from the local authorities, the network will distribute them free of charge to farmers earning less than $10,000 a year, and these farmers will be allowed to save and reuse seed from one crop to the next. In many prospective countries, however, locally adapted varieties cannot yet be developed and tested because the countries lack the proper biosafety procedures required by the international convention on biodiversity.

Challenges remain. Golden Rice must still be tested for environmental and food safety. In addition, human testing is necessary to determine how well the body absorbs the beta-carotene. The effects of storage and cooking must also be assessed. It is not clear how consumers will react to the color of Golden Rice, especially in cultures that prefer white rice. Field tests are scheduled to begin in Asia later this year. No one expects Golden Rice to be a magic bullet for malnutrition. But it could be a cost-effective supplement to other strategies.

Economic Evidence

The ultimate success or failure of transgenic crops will depend on whether farmers gain economic benefits from using them. Even when the private-sector research is well suited to conditions in a developing country, access to the technology may be expensive. The contrasting cases of insect-resistant Bt cotton and herbicide-tolerant soybeans in Argentina reveal how the high price of patented technology can stymie progress. Monsanto, which developed both types of cultivar, patented its cotton innovation in Argentina but failed to do so with its soybeans. The company has thus been able to charge a significantly higher price for its Bt cottonseed than for conventional cottonseed. Consequently, the transgenic cotton offers relatively little benefit to Argentine farmers, who have not adopted it widely.

KEY GM CROPS

Herbicide-tolerant soybeans fill the majority of genetically modified (GM) crop area in the world, including major plantings in South America.

Maize is a staple food in some developing countries and is also used as animal feed. It is sometimes grown in rotation with soybeans.

Rice is the primary staple food in much of the developing world, yet virtually no transgenic rice is under commercial cultivation.

Orphan crops—regional staple foods such as sorghum, pearl millet and pigeon pea—are being neglected by both biotechnology and conventional agricultural research programs.

ENVISION/CORBIS (*soy*); ED YOUNG *Corbis* (*maize*); KIEFER/PHOTOCUISINE/CORBIS (*rice*)

In contrast, Argentine farmers have enthusiastically embraced transgenic soybeans, for which less expensive seed (that Monsanto has not patented) is available. On average, productivity increased 10 percent on adopting farms, with the growers receiving nine tenths of the economic benefits. Globally, farmers receive only about 13 percent of the benefits of transgenic soybeans, with consumers taking 53 percent (through lower food prices) and seed and biotechnology firms 34 percent. Economists have credited the relatively cheap transgenics as the major factor in transforming soybean farming in Argentina, including a tremendous increase in the production of soybeans, the widespread adoption of no-till agriculture and the growing of soybeans in rotation with maize. No-till farming, in which farmers leave crop residues in place instead of tilling them into the earth, protects the soil from erosion and compaction and promotes the accumulation of organic matter. No-till farming is more practical with herbicide-tolerant crops, which allow farmers to control weeds with herbicides rather than tillage.

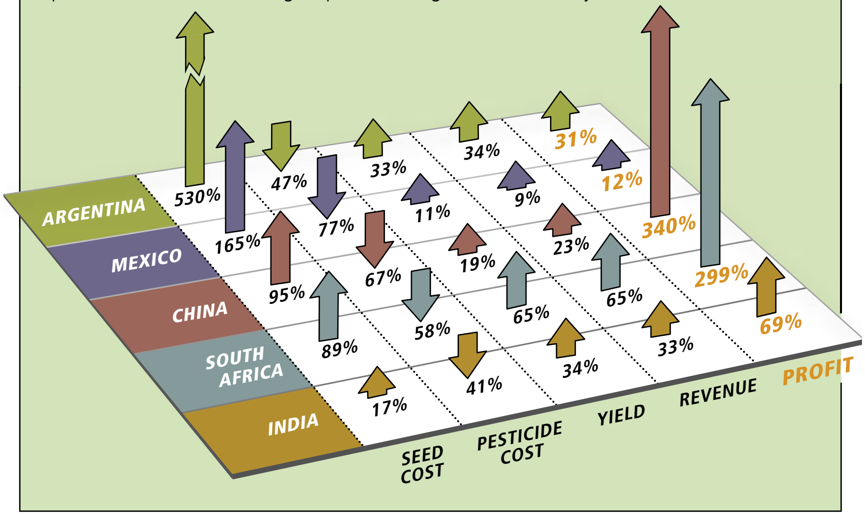
Yet the Argentine experience with soybeans does not present a model for solving the problem of access to biotech advances more generally. The protection of intellectual-property rights—through patents or other means—provides necessary incentives for technology developers and has greatly stimulated the growth of private agricultural research (albeit not necessarily in Argentina, as the private sector has simply brought into the country technologies developed in the U.S. and Europe). Existing public-sector international networks for sharing technologies across countries are being used less and less, however. The urgent need today is for a system of technology flows that preserves the incentives for private-sector innovation while at the same time meeting the needs of poor farmers in the developing world.

Otherwise countries must do as China has done. China has achieved success through its highly developed public agricultural research system, which has independently produced in-

[SOLID DATA]

THE TRANSGENIC ADVANTAGE

The experience of cotton farmers in five developing nations shows that even though the seed costs for a genetically modified crop can be much higher than for a conventional one, lower pesticide costs and higher yields and revenues can make the modified crops more profitable. The profits were very different, however, from country to country. In Argentina, seed costs took much of the substantial economic benefits away from the farmers. In China, competition from locally developed seeds kept seed prices relatively lower. Farmers there profited tremendously by slashing their heavy pesticide use. Mexico achieved only marginal yield gains. Also (not reflected in this chart) in many regions of Mexico few farmers adopted the transgenic cotton because of its poor effectiveness against the species of insects threatening crops in their region of the country.



sect-resistant crops by using a gene from cowpeas. Researchers have incorporated the gene into a large number of locally adapted cotton varieties that compete directly with Monsanto's Bt cotton. As a result, transgenic seed prices are much lower in China than elsewhere, and farmers reap substantially higher returns. In terms of productivity, farmer incomes, equity and sustainability, the 7.5 million small farmers who are growing insect-resistant cotton in China represent the most successful case so far of transgenic crop adoption in the developing world. The role of the public sector in developing and distributing the Chinese cotton varieties has been instrumental in achieving that success.

Chinese growers of transgenic cotton experience lower yield gains than in many other countries because pest damage on conventional cotton is controlled by heavy pesticide use in China. The farmers nonetheless achieve large net profit gains because their marginally higher yields are accompanied by much lower pesticide costs and only moderately higher seed costs. The significant reduction in pesticide use on cotton also has important benefits for the environment and for the farmers' health.

A 2003 analysis by Carl Pray of Rutgers University and Jikun Huang of the Center for Chinese Agricultural Policy concluded that the benefits of transgenic cotton in China were decidedly pro-poor: the smallest farms experienced the largest yield gains, and midsize farms had the largest reductions in total costs as a result of less pesticide use. In terms of net income, the percentage gains for small and midsize farms were more than twice those for the largest farms.

Our focus on cotton may seem odd in an article on reducing hunger, but it comes about because the most extensive peer-reviewed studies published to date on the outcomes of transgenic crop adoption in developing countries have been for insect-resistant cotton in Argentina, China, India, Mexico and South Africa [*see box at left*]. As far as foodstuffs go, such studies have been published only for soybeans and maize in Argentina and maize in South Africa.

The data for cotton crops are nonetheless highly relevant because they provide lessons in the economics of genetic modification that will be applicable to food crops. In addition, the cotton itself can improve the food security of many people: it can not only increase the cotton farmers' incomes but also raise the incomes of many other poor people in the wider economy when these farmers hire more laborers and buy more rural goods and services.

South Africa provides another important lesson about the role of institutions. That country has large, modern commercial farms operating alongside small-holder semisubsistence farms. Insect-resistant cotton and yellow maize (primarily used as animal feed) were introduced as long ago as 1998, and in 2001 South Africa became the first developing country to plant a genetically modified staple food (white maize).

For cotton, two studies of small-holder farmers in the Makhathini Flats of KwaZulu-Natal province in Africa have found that adopters of transgenics benefited economically. A local cooperative provided seed on credit, along with technical advice. The benefits were widely shared by all farm types, and both studies found significant pro-poor benefits. Pesticide use declined significantly, bringing both environmental and health benefits: cases of pesticide burns and sickness treated at local hospitals declined from about 150 cases in 1998–1999, when adoption was very limited, to about a dozen by 2001–2002, when adoption had become widespread.

The Makhathini Flats success story was not sustained, however. The local cooperative also

JEN CHRISTIANSEN; SOURCE: "ECONOMIC IMPACT OF TRANSGENIC CROPS IN DEVELOPING COUNTRIES," BY TERRI RANEY, IN *CURRENT OPINION IN BIOTECHNOLOGY*, VOL. 17, NO. 2, PAGES 174–178; APRIL 2006

[CONCERNS]

POTENTIAL HAZARDS

Opposition to genetically modified crops or their products by consumers and advocacy groups, based on worries about food safety and harm to the environment, threatens to frustrate efforts to use biotechnology to alleviate poverty and hunger. The problem can be acute for developing countries, which often lack the capacity to formulate and implement their own regulatory procedures. International protocols do not permit transgenic organisms to enter a country or to be developed there if the country lacks appropriate regulatory procedures.

ACTIVISTS in Mexico City protest the lack of information on labels of corn flour products containing genetically modified corn.

The chief food-safety concerns are fears that allergens or toxins may be present and that other unintentional changes in the food composition may occur. Yet to date no verifiable toxic or nutritionally deleterious effects resulting from the consumption of transgenic foods have been discovered anywhere in the world. National food-safety authorities of several countries have evaluated the transgenic crops currently being grown commercially and the foods derived from them, using procedures based on internationally agreed upon principles, and have judged them all safe to eat.

Environmental concerns center on the spread of transgenes to related crops or weeds ("gene flow"), the development of herbicide-resistant weeds, the development of insect pests resistant to the Bt toxin (which has long been used as a pesticide, particularly by organic farmers), harm by insect-resistant crops to nontarget organisms, and indirect environmental effects that come about because transgenic crops lead to different cropping practices.

Scientists disagree about the likelihood and potential consequences of these hazards. Gene flow, for example, is acknowledged to be possible when transgenic crops are grown close to related plants, but the transgenes will persist and spread only if they give the recipient plant a competitive advantage. Such gene flow could inflict economic harm by, for instance, making a product ineligible for a status such as "organic." What would suffice to constitute ecological harm is more controversial.

Thus far, none of the major environmental hazards potentially associated with transgenic crops has developed in commercial fields. Herbicide-resistant weeds have been observed—although not necessarily caused by growing transgenic crops—and so far they can be managed by alternative herbicides. The lack of negative impacts so far does not mean they cannot occur, of course. Scientific understanding of ecological and food-safety processes is incomplete, but many of the risks highlighted for transgenics are similar to risks inherent in conventional agriculture as well. Careful, case-by-case evaluation of new crops (especially ones developed using new techniques, such as modification of multiple transgenes) must continue in order to minimize the potential for problems to emerge. *—T.R. and P.P.*

SCI AM For a longer discussion of the scientific consensus about the various safety and environmental concerns, log on to:
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ran the only cotton gin in the area, thereby ensuring a high rate of debt recovery. When another cotton gin opened in the region, the cooperative was no longer guaranteed repayment of its debts and ceased providing the transgenic seed on credit in 2002–2003. Cotton production in the region fell drastically. Researchers concluded that Bt plants could be an excellent technology for African countries but warned that institutional failure like that in the Makhathini Flats is the norm rather than the exception in Africa.

The Makhathini Flats example has relevance not just for Africa. No technology can overcome the gaps in infrastructure, regulation, markets, seed distribution systems and extension services that hamper growth in agricultural productivity, especially for poor farmers in remote areas. Transgenic crops ought to be seen as one tool within a broader agricultural development strategy.

The ability of scientists to devise safe, effective transgenic crops for a gene revolution seems assured. What remains in doubt for a hungry person in a developing country is how long it will be before someone develops seeds suitable for farms in his or her province and those seeds become available on sufficiently attractive terms for local farmers to adopt them. ■

ANDREW WINNING *Reuters*

OVERCOMING INSTITUTIONAL OBSTACLES

Developing countries need basic plant breeding capacity to adapt imported transgenic technologies into local crop varieties.

Countries need to adopt science-based, transparent and predictable regulatory procedures for testing the safety and efficacy of transgenic crops.

Companies and regulatory authorities should make public the results of their safety testing to minimize unnecessary duplication of tests done elsewhere.

Harmonization and mutual recognition of regulatory procedures at the regional and global level could help minimize unnecessary duplication and expense.

The protection of intellectual-property rights (IPRs) needs to balance the needs of technology developers and users (such as farmers). Possibilities include IPR clearinghouses and "open-source" sharing of technologies (such as www.bios.net).

➡ MORE TO EXPLORE

Agricultural Biotechnology: Meeting the Needs of the Poor? The State of Food and Agriculture 2003–04. FAO; 2004.

Poorer Nations Turn to Publicly Developed GM Crops. Joel Cohen in *Nature Biotechnology,* Vol. 23, No. 1, pages 27–33; January 2005.

From the Green Revolution to the Gene Revolution: How Will the Poor Fare? Prabhu Pingali and Terri Raney. ESA Working Paper No. 05-09. FAO; November 2005.

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TIME

Monday, Jul. 31, 2000

This Rice Could Save a Million Kids a Year

By J. Madeleine Nash / Zurich

At first, the grains of rice that Ingo Potrykus sifted through his fingers did not seem at all special, but that was because they were still encased in their dark, crinkly husks. Once those drab coverings were stripped away and the interiors polished to a glossy sheen, Potrykus and his colleagues would behold the seeds' golden secret. At their core, these grains were not pearly white, as ordinary rice is, but a very pale yellow--courtesy of beta-carotene, the nutrient that serves as a building block for vitamin A.

Potrykus was elated. For more than a decade he had dreamed of creating such a rice: a golden rice that would improve the lives of millions of the poorest people in the world. He'd visualized peasant farmers wading into paddies to set out the tender seedlings and winnowing the grain at harvest time in handwoven baskets. He'd pictured small children consuming the golden gruel their mothers would make, knowing that it would sharpen their eyesight and strengthen their resistance to infectious diseases.

And he saw his rice as the first modest start of a new green revolution, in which ancient food crops would acquire all manner of useful properties: bananas that wouldn't rot on the way to market; corn that could supply its own fertilizer; wheat that could thrive in drought-ridden soil.

But imagining a golden rice, Potrykus soon found, was one thing and bringing one into existence quite another. Year after year, he and his colleagues ran into one unexpected obstacle after another, beginning with the finicky growing habits of the rice they transplanted to a greenhouse near the foothills of the Swiss Alps. When success finally came, in the spring of 1999, Potrykus was 65 and about to retire as a full professor at the Swiss Federal Institute of Technology in Zurich. At that point, he tackled an even more formidable challenge.

Having created golden rice, Potrykus wanted to make sure it reached those for whom it was intended: malnourished children of the developing world. And that, he knew, was not likely to be easy. Why? Because in addition to a full complement of genes from Oryza sativa--the Latin name for the most commonly consumed species of rice--the golden grains also contained snippets of DNA borrowed from bacteria and daffodils. It was what some would call Frankenfood, a product of genetic engineering. As such, it was entangled in a web of hopes and fears and political baggage, not to mention a fistful of ironclad patents.

For about a year now--ever since Potrykus and his chief collaborator, Peter Beyer of the University of Freiburg in Germany, announced their achievement--their golden grain has illuminated an increasingly polarized public debate. At issue is the question of what genetically engineered crops represent. Are they, as their proponents argue, a technological leap forward that will bestow incalculable benefits on the world and its people? Or do they represent a perilous step down a slippery slope that will lead to ecological and agricultural ruin? Is genetic engineering just a more efficient way to do the business of conventional crossbreeding? Or does the ability to mix the genes of any species--even plants and animals--give man more power than he should have?

The debate erupted the moment genetically engineered crops made their commercial debut in the mid-1990s, and it has escalated ever since. First to launch major protests against biotechnology were European environmentalists and consumer-advocacy groups. They were soon followed by their U.S. counterparts, who made a big splash at last fall's World Trade Organization meeting in Seattle and last week launched an offensive designed to target one company after another (see accompanying story). Over the coming months, charges that transgenic crops pose grave dangers will be raised in petitions, editorials, mass mailings and protest marches. As a result, golden rice, despite its humanitarian intent, will probably be subjected to the same kind of hostile scrutiny that has already led to curbs on the commercialization of these crops in Britain, Germany, Switzerland and Brazil.

The hostility is understandable. Most of the genetically engineered crops introduced so far represent minor variations on the same two themes: resistance to insect pests and to herbicides used to control the growth of weeds. And they are often marketed by large, multinational corporations that produce and sell the very agricultural chemicals farmers are spraying on their fields. So while many farmers have embraced such crops as Monsanto's Roundup Ready soybeans, with their genetically engineered resistance to Monsanto's Roundup-brand herbicide, that let them spray weed killer without harming crops, consumers have come to regard such things with mounting suspicion. Why resort to a strange new technology that might harm the biosphere, they ask, when the benefits of doing so seem small?

Indeed, the benefits have seemed small--until golden rice came along to suggest otherwise. Golden rice is clearly not the moral equivalent of Roundup Ready beans. Quite the contrary, it is an example--the first compelling example--of a genetically engineered crop that may benefit not just the farmers who grow it but also the consumers who eat it. In this case, the consumers include at least a million children who die every year because they are weakened by vitamin-A deficiency and an additional 350,000 who go blind.

No wonder the biotech industry sees golden rice as a powerful ally in its struggle to win public acceptance. No wonder its critics see it as a cynical ploy. And no wonder so many of those concerned about the twin evils of poverty and hunger look at golden rice and see reflected in it their own passionate conviction that genetically engineered crops can be made to serve the greater public good--that in fact such crops have a critical role to play in feeding a world that is about to add to its present population of 6 billion. As former President Jimmy Carter put it, "Responsible biotechnology is not the enemy; starvation is."

Indeed, by the year 2020, the demand for grain, both for human consumption and for animal feed, is projected to go up by nearly half, while the amount of arable land available to satisfy that demand will not only grow much more slowly but also, in some areas, will probably dwindle. Add to that the need to conserve overstressed water resources and reduce the use of polluting chemicals, and the enormity of the challenge becomes apparent. In order to meet it, believes Gordon Conway, the agricultural ecologist who heads the Rockefeller Foundation, 21st century farmers will have to draw on every arrow in their agricultural quiver, including genetic engineering. And contrary to public perception, he says, those who have the least to lose and the most to gain are not well-fed Americans and Europeans but the hollow-bellied citizens of the developing world.

GOING FOR THE GOLD

It was in the late 1980s, after he became a full professor of plant science at the Swiss Federal Institute of Technology, that Ingo Potrykus started to think about using genetic engineering to improve the nutritional qualities of rice. He knew that of some 3 billion people who depend on rice as their major staple, around 10% risk some degree of vitamin-A deficiency and the health problems that result. The reason, some alleged, was an overreliance on rice ushered in by the green revolution. Whatever its cause, the result was distressing: these people were so poor that they ate a few bowls of rice a day and almost nothing more.

The problem interested Potrykus for a number of reasons. For starters, he was attracted by the scientific challenge of transferring not just a single gene, as many had already done, but a group of genes that represented a key part of a biochemical pathway. He was also motivated by complex emotions, among them empathy. Potrykus knew more than most what it meant not to have enough to eat. As a child growing up in war-ravaged Germany, he and his brothers were often so desperately hungry that they ate what they could steal.

Around 1990, Potrykus hooked up with Gary Toenniessen, director of food security for the Rockefeller Foundation. Toenniessen had identified the lack of beta-carotene in polished rice grains as an appropriate target for gene scientists like Potrykus to tackle because it lay beyond the ability of traditional plant breeding to address. For while rice, like other green plants, contains light-trapping beta-carotene in its external tissues, no plant in the entire Oryza genus--as far as anyone knew--produced beta-carotene in its endosperm (the starchy interior part of the rice grain that is all most people eat).

It was at a Rockefeller-sponsored meeting that Potrykus met the University of Freiburg's Peter Beyer, an expert on the beta-carotene pathway in daffodils. By combining their expertise, the two scientists figured, they might be able to remedy this unfortunate oversight in nature. So in 1993, with some $100,000 in seed money from the Rockefeller Foundation, Potrykus and Beyer launched what turned into a seven-year, $2.6 million project, backed also by the Swiss government and the European Union. "I was in a privileged situation," reflects Potrykus, "because I was able to operate without industrial support. Only in that situation can you think of giving away your work free."

That indeed is what Potrykus announced he and Beyer planned to do. The two scientists soon discovered, however, that giving away golden rice was not going to be as easy as they thought. The genes they transferred and the bacteria they used to transfer those genes were all encumbered by patents and proprietary rights. Three months ago, the two scientists struck a deal with AstraZeneca, which is based in London and holds an exclusive license to one of the genes Potrykus and Beyer used to create golden rice. In exchange for commercial marketing rights in the U.S. and other affluent markets, AstraZeneca agreed to lend its financial muscle and legal expertise to the cause of putting the seeds into the hands of poor farmers at no charge.

No sooner had the deal been made than the critics of agricultural biotechnology erupted. "A rip-off of the public trust," grumbled the Rural Advancement Foundation International, an advocacy group based in Winnipeg, Canada. "Asian farmers get (unproved) genetically modified rice, and AstraZeneca gets the 'gold.'" Potrykus was dismayed by such negative reaction. "It would be irresponsible," he exclaimed, "not to say immoral, not to use biotechnology to try to solve this problem!" But such expressions of good intentions would not be enough to allay his opponents' fears.

WEIGHING THE PERILS

Beneath the hyperbolic talk of Frankenfoods and Superweeds, even proponents of agricultural biotechnology agree, lie a number of real concerns. To begin with, all foods, including the transgenic foods created through genetic engineering, are potential sources of allergens. That's because the transferred genes contain instructions for making proteins, and not all proteins are equal. Some--those in peanuts, for example--are well known for causing allergic reactions. To many, the possibility that golden rice might cause such a problem seems farfetched, but it nonetheless needs to be considered.

Then there is the problem of "genetic pollution," as opponents of biotechnology term it. Pollen grains from such wind-pollinated plants as corn and canola, for instance, are carried far and wide. To farmers, this mainly poses a nuisance. Transgenic canola grown in one field, for example, can very easily pollinate nontransgenic plants grown in the next. Indeed this is the reason behind the furor that recently erupted in Europe when it was discovered that canola seeds from Canada--unwittingly planted by farmers in England, France, Germany and Sweden--contained transgenic contaminants.

The continuing flap over Bt corn and cotton--now grown not only in the U.S. but also in Argentina and China--has provided more fodder for debate. Bt stands for a common soil bacteria, Bacillus thuringiensis, different strains of which produce toxins that target specific insects. By transferring to corn and cotton the bacterial gene responsible for making this toxin, Monsanto and other companies have produced crops that are resistant to the European corn borer and the cotton bollworm. An immediate concern, raised by a number of ecologists, is whether or not widespread planting of these crops will spur the development of resistance to Bt among crop pests. That would be unfortunate, they point out, because Bt is a safe and effective natural insecticide that is popular with organic farmers.

Even more worrisome are ecological concerns. In 1999 Cornell University entomologist John Losey performed a provocative, "seat-of-the-pants" laboratory experiment. He dusted Bt corn pollen on plants populated by monarch-butterfly caterpillars. Many of the caterpillars died. Could what happened in Losey's laboratory happen in cornfields across the Midwest? Were these lovely butterflies, already under pressure owing to human encroachment on their Mexican wintering grounds, about to face a new threat from high-tech farmers in the north?

The upshot: despite studies pro and con--and countless save-the-monarch protests acted out by children dressed in butterfly costumes--a conclusive answer to this question has yet to come. Losey himself is not yet convinced that Bt corn poses a grave danger to North America's monarch-butterfly population, but he does think the issue deserves attention. And others agree. "I'm not anti biotechnology per se," says biologist Rebecca Goldberg, a senior scientist with the Environmental Defense Fund, "but I would like to have a tougher regulatory regime. These crops should be subject to more careful screening before they are released."

Are there more potential pitfalls? There are. Among other things, there is the possibility that as transgenes in pollen drift, they will fertilize wild plants, and weeds will emerge that are hardier and even more difficult to control. No one knows how common the exchange of genes between domestic plants and their wild relatives really is, but Margaret Mellon, director of the Union of Concerned Scientists' agriculture and biotechnology program, is certainly not alone in thinking that it's high time we find out. Says she: "People should be responding to these concerns with experiments, not assurances."

And that is beginning to happen, although--contrary to expectations--the reports coming in are not necessarily that scary. For three years now, University of Arizona entomologist Bruce Tabashnik has been monitoring fields of Bt cotton that farmers have planted in his state. And in this instance at least, he says, "the environmental risks seem minimal, and the benefits seem great." First of all, cotton is self-pollinated rather than wind-pollinated, so that the spread of the Bt gene is of less concern. And because the Bt gene is so effective, he notes, Arizona farmers have reduced their use of chemical insecticides 75%. So far, the pink bollworm population has not rebounded, indicating that the feared resistance to Bt has not yet developed.

ASSESSING THE PROMISE

Are the critics of agricultural biotechnology right? Is biotech's promise nothing more than overblown corporate hype? The papaya growers in Hawaii's Puna district clamor to disagree. In 1992 a wildfire epidemic of papaya ringspot virus threatened to destroy the state's papaya industry; by 1994, nearly half the state's papaya acreage had been infected, their owners forced to seek outside employment. But then help arrived, in the form of a virus-resistant transgenic papaya developed by Cornell University plant pathologist Dennis Gonsalves.

In 1995 a team of scientists set up a field trial of two transgenic lines--UH SunUP and UH Rainbow--and by 1996, the verdict had been rendered. As everyone could see, the nontransgenic plants in the field trial were a stunted mess, and the transgenic plants were healthy. In 1998, after negotiations with four patent holders, the papaya growers switched en masse to the transgenic seeds and reclaimed their orchards. "Consumer acceptance has been great," reports Rusty Perry, who runs a papaya farm near Puna. "We've found that customers are more concerned with how the fruits look and taste than with whether they are transgenic or not."

Viral diseases, along with insect infestations, are a major cause of crop loss in Africa, observes Kenyan plant scientist Florence Wambugu. African sweet-potato fields, for example, yield only 2.4 tons per acre, vs. more than double that in the rest of the world. Soon Wambugu hopes to start raising those yields by introducing a transgenic sweet potato that is resistant to the feathery mottle virus. There really is no other option, explains Wambugu, who currently directs the International Service for the Acquisition of Agri-biotech Applications in Nairobi. "You can't control the virus in the field, and you can't breed in resistance through conventional means."

To Wambugu, the flap in the U.S. and Europe over genetically engineered crops seems almost ludicrous. In Africa, she notes, nearly half the fruit and vegetable harvest is lost because it rots on the way to market. "If we had a transgenic banana that ripened more slowly," she says, "we could have 40% more bananas than now." Wambugu also dreams of getting access to herbicide-resistant crops. Says she: "We could liberate so many people if our crops were resistant to herbicides that we could then spray on the surrounding weeds. Weeding enslaves Africans; it keeps children from school."

In Wambugu's view, there are more benefits to be derived from agricultural biotechnology in Africa than practically anywhere else on the planet--and this may be so. Among the genetic-engineering projects funded by the Rockefeller Foundation is one aimed at controlling striga, a weed that parasitizes the roots of African corn plants. At present there is little farmers can do about striga infestation, so tightly intertwined are the weed's roots with the roots of the corn plants it targets. But scientists have come to understand the source of the problem: corn roots exude chemicals that attract striga. So it may prove possible to identify the genes that are responsible and turn them off.

The widespread perception that agricultural biotechnology is intrinsically inimical to the environment perplexes the Rockefeller Foundation's Conway, who views genetic engineering as an important tool for achieving what he has termed a "doubly green revolution." If the technology can marshal a plant's natural defenses against weeds and viruses, if it can induce crops to flourish with minimal application of chemical fertilizers, if it can make dryland agriculture more productive without straining local water supplies, then what's wrong with it?

Of course, these particular breakthroughs have not happened yet. But as the genomes of major crops are ever more finely mapped, and as the tools for transferring genes become ever more precise, the possibility for tinkering with complex biochemical pathways can be expected to expand rapidly. As Potrykus sees it, there is no question that agricultural biotechnology can be harnessed for the good of humankind. The only question is whether there is the collective will to do so. And the answer may well emerge as the people of the world weigh the future of golden rice.

--With reporting by Simon Robinson/Nairobi

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Lecture to Oxford Farming Conference, 3 January 2013

3 January 2013 **323 comments**

Lecture to Oxford Farming Conference, 3 January 2013

[Please check against delivery - see video below for speech as given.]

07 Mark Lynas from **Oxford Farming Conference** on **Vimeo**.

I want to start with some apologies. For the record, here and upfront, I apologise for having spent several years ripping up GM crops. I am also sorry that I helped to start the anti-GM movement back in the mid 1990s, and that I thereby assisted in demonising an important technological option which can be used to benefit the environment.

As an environmentalist, and someone who believes that everyone in this world has a right to a healthy and nutritious diet of their choosing, I could not have chosen a more counter-productive path. I now regret it completely.

So I guess you'll be wondering – what happened between 1995 and now that made me not only change my mind but come here and admit it? Well, the answer is fairly simple: I discovered science, and in the process I hope I became a better environmentalist.

When I first heard about Monsanto's GM soya I knew exactly what I thought. Here was a big American corporation with a nasty track record, putting something new and experimental into our food without telling us. Mixing genes between species seemed to be about as unnatural as

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you can get – here was humankind acquiring too much technological power; something was bound to go horribly wrong. These genes would spread like some kind of living pollution. It was the stuff of nightmares.

These fears spread like wildfire, and within a few years GM was essentially banned in Europe, and our worries were exported by NGOs like Greenpeace and Friends of the Earth to Africa, India and the rest of Asia, where GM is still banned today. This was the most successful campaign I have ever been involved with.

This was also explicitly an anti-science movement. We employed a lot of imagery about scientists in their labs cackling demonically as they tinkered with the very building blocks of life. Hence the Frankenstein food tag – this absolutely was about deep-seated fears of scientific powers being used secretly for unnatural ends. What we didn't realise at the time was that the real Frankenstein's monster was not GM technology, but our reaction against it.

For me this anti-science environmentalism became increasingly inconsistent with my pro-science environmentalism with regard to climate change. I published my first book on global warming in 2004, and I was determined to make it scientifically credible rather than just a collection of anecdotes.

So I had to back up the story of my trip to Alaska with satellite data on sea ice, and I had to justify my pictures of disappearing glaciers in the Andes with long-term records of mass balance of mountain glaciers. That meant I had to learn how to read scientific papers, understand basic statistics and become literate in very different fields from oceanography to paleoclimate, none of which my degree in politics and modern history helped me with a great deal.

I found myself arguing constantly with people who I considered to be incorrigibly anti-science, because they wouldn't listen to the climatologists and denied the scientific reality of climate change. So I lectured them about the value of peer-review, about the importance of scientific consensus and how the only facts that mattered were the ones published in the most distinguished scholarly journals.

My second climate book, Six Degrees, was so sciency that it even won the Royal Society science books prize, and climate scientists I had become friendly with would joke that I knew more about the subject than them. And yet, incredibly, at this time in 2008 I was still penning screeds in the Guardian attacking the science of GM – even though I had done no academic research on the topic, and had a pretty limited personal understanding. I don't think I'd ever read a peer-reviewed paper on biotechnology or plant science even at this late stage.

Obviously this contradiction was untenable. What really threw me were some of the comments underneath my final anti-GM Guardian article. In particular one critic said to me: so you're opposed to GM on the basis that it is marketed by big corporations. Are you also opposed to the wheel because because it is marketed by the big auto companies?

So I did some reading. And I discovered that one by one my cherished beliefs about GM turned out to be little more than green urban myths.

I'd assumed that it would increase the use of chemicals. It turned out that pest-resistant cotton and maize needed less insecticide.

I'd assumed that GM benefited only the big companies. It turned out that billions of dollars of benefits were accruing to farmers needing fewer inputs.

I'd assumed that Terminator Technology was robbing farmers of the right to save seed. It turned out that hybrids did that long ago, and that Terminator never happened.

I'd assumed that no-one wanted GM. Actually what happened was that Bt cotton was pirated into India and roundup ready soya into Brazil because farmers were so eager to use them.

I'd assumed that GM was dangerous. It turned out that it was safer and more precise than conventional breeding using mutagenesis for example; GM just moves a couple of genes, whereas conventional breeding mucks about with the entire genome in a trial and error way.

But what about mixing genes between unrelated species? The fish and the tomato? Turns out viruses do that all the time, as do plants and insects and even us – it's called gene flow.

But this was still only the beginning. So in my third book The God Species I junked all the environmentalist orthodoxy at the outset and tried to look at the bigger picture on a planetary scale.

And this is the challenge that faces us today: we are going to have to feed 9.5 billion hopefully much less poor people by 2050 on about the same land area as we use today, using limited fertiliser, water and pesticides and in the context of a rapidly-changing climate.

Let's unpack this a bit. I know in a previous year's lecture in this conference there was the topic of population growth. This area too is beset by myths. People think that high rates of fertility in the developing world are the big issue – in other words, poor people are having too many children, and we therefore need either family planning or even something drastic like mass one-child policies.

The reality is that global average fertility is down to about 2.5 – and if you consider that natural replacement is 2.2, this figure is not much above that. So where is the massive population growth coming from? It is coming because of declining infant mortality – more of today's youngsters are growing up to have their own children rather than dying of preventable diseases in early childhood.

The rapid decline in infant mortality rates is one of the best news stories of our decade and the heartland of this great success story is sub-Saharan Africa. It's not that there are legions more children being born – in fact, in the words of Hans Rosling, we are already at 'peak child'. That is, about 2 billion children are alive today, and there will never be more than that because of declining fertility.

But so many more of these 2 billion children will survive into adulthood today to have their own children. They are the parents of the young adults of 2050. That's the source of the 9.5 billion population projection for 2050. You don't have to have lost a child, God forbid, or even be a parent, to know that declining infant mortality is a good thing.

So how much food will all these people need? According to the latest projections, published last year in the Proceedings of the National Academy of Sciences, we are looking at a global demand increase of well over 100% by mid-century. This is almost entirely down to GDP growth, especially in developing countries.

In other words, we need to produce more food not just to keep up with population but because poverty is gradually being eradicated, along with the widespread malnutrition that still today means close to 800 million people go to bed hungry each night. And I would challenge anyone in a rich country to say that this GDP growth in poor countries is a bad thing.

But as a result of this growth we have very serious environmental challenges to tackle. Land conversion is a large source of greenhouse gases, and perhaps the greatest source of biodiversity loss. This is another reason why intensification is essential – we have to grow more on limited land in order to save the rainforests and remaining natural habitats from the plough.

We also have to deal with limited water – not just depleting aquifers but also droughts that are expected to strike with increasing intensity in the agricultural heartlands of continents thanks to climate change. If we take more water from rivers we accelerate biodiversity loss in these fragile habitats.

We also need to better manage nitrogen use: artificial fertiliser is essential to feed humanity, but its inefficient use means dead zones in the Gulf of Mexico and many coastal areas around the world, as well as eutrophication in fresh water ecosystems.

It is not enough to sit back and hope that technological innovation will solve our problems. We have to be much more activist and strategic than that. We have to ensure that technological innovation moves much more rapidly, and in the right direction for those who most need it.

In a sense we've been here before. When Paul Ehrlich published the Population Bomb in 1968, he wrote: "The battle to feed all of humanity is over. In the 1970s hundreds of millions of people will starve to death in spite of any crash programs embarked upon now." The advice was explicit – in basket-case countries like India, people might as well starve sooner rather than later, and therefore food aid to them should be eliminated to reduce population growth.

It was not pre-ordained that Ehrlich would be wrong. In fact, if everyone had heeded his advice hundreds of millions of people might well have died needlessly. But in the event, malnutrition was cut dramatically, and India became food self-sufficient, thanks to Norman Borlaug and his Green Revolution.

It is important to recall that Borlaug was equally as worried about population growth as Ehrlich. He just thought it was worth trying to do something about it. He was a pragmatist because he believed in doing what was possible, but he was also an idealist because he believed that people everywhere deserved to have enough to eat.

So what did Norman Borlaug do? He turned to science and technology. Humans are a tool-making species – from clothes to ploughs, technology is primarily what distinguishes us from other apes. And much of this work was focused on the genome of major domesticated crops – if wheat, for example, could be shorter and put more effort into seed-making rather than stalks, then yields would improve and grain loss due to lodging would be minimised.

Before Borlaug died in 2009 he spent many years campaigning against those who for political and ideological reasons oppose modern innovation in agriculture. To quote: “If the naysayers do manage to stop agricultural biotechnology, they might actually precipitate the famines and the crisis of global biodiversity they have been predicting for nearly 40 years.”

And, thanks to supposedly environmental campaigns spread from affluent countries, we are perilously close to this position now. Biotechnology has not been stopped, but it has been made prohibitively expensive to all but the very biggest corporations.

It now costs tens of millions to get a crop through the regulatory systems in different countries. In fact the latest figures I’ve just seen from CropLife suggest it costs $139 million to move from discovering a new crop trait to full commercialisation, so open-source or public sector biotech really does not stand a chance.

There is a depressing irony here that the anti-biotech campaigners complain about GM crops only being marketed by big corporations when this is a situation they have done more than anyone to help bring about.

In the EU the system is at a standstill, and many GM crops have been waiting a decade or more for approval but are permanently held up by the twisted domestic politics of anti-biotech countries like France and Austria. Around the whole world the regulatory delay has increased to more than 5 and a half years now, from 3.7 years back in 2002. The bureaucratic burden is getting worse.

France, remember, long refused to accept the potato because it was an American import. As one commentator put it recently, Europe is on the verge of becoming a food museum. We well-fed consumers are blinded by romantic nostalgia for the traditional farming of the past. Because we have enough to eat, we can afford to indulge our aesthetic illusions.

But at the same time the growth of yields worldwide has stagnated for many major food crops, as research published only last month by Jonathan Foley and others in the journal *Nature Communications* showed. If we don’t get yield growth back on track we are indeed going to have trouble keeping up with population growth and resulting demand, and prices will rise as well as more land being converted from nature to agriculture.

To quote Norman Borlaug again: “I now say that the world has the technology — either available or well advanced in the research pipeline — to feed on a sustainable basis a population of 10 billion people. The more pertinent question today is whether farmers and ranchers will be permitted to use this new technology? While the affluent nations can certainly afford to adopt ultra low-risk positions, and pay more for food produced by the so-called ‘organic’ methods, the one billion chronically undernourished people of the low income, food-deficit nations cannot.”

As Borlaug was saying, perhaps the most pernicious myth of all is that organic production is better, either for people or the environment. The idea that it is healthier has been repeatedly disproved in the scientific literature. We also know from many studies that organic is much less productive, with up to 40-50% lower yields in terms of land area. The Soil Association went to great lengths in a recent report on feeding the world with organic not to mention this productivity gap.

Nor did it mention that overall, if you take into account land displacement effects, organic is also likely worse for biodiversity. Instead they talk about an ideal world where people in the west eat less meat and fewer calories overall so that people in developing countries can have more. This is simplistic nonsense.

If you think about it, the organic movement is at its heart a rejectionist one. It doesn't accept many modern technologies on principle. Like the Amish in Pennsylvania, who froze their technology with the horse and cart in 1850, the organic movement essentially freezes its technology in somewhere around 1950, and for no better reason.

It doesn't even apply this idea consistently however. I was reading in a recent Soil Association magazine that it is OK to blast weeds with flamethrowers or fry them with electric currents, but benign herbicides like glyphosate are still a no-no because they are 'artificial chemicals'.

In reality there is no reason at all why avoiding chemicals should be better for the environment – quite the opposite in fact. Recent research by Jesse Ausubel and colleagues at Rockefeller University looked at how much extra farmland Indian farmers would have had to cultivate today using the technologies of 1961 to get today's overall yield. The answer is 65 million hectares, an area the size of France.

In China, maize farmers spared 120 million hectares, an area twice the size of France, thanks to modern technologies getting higher yields. On a global scale, between 1961 and 2010 the area farmed grew by only 12%, whilst kilocalories per person rose from 2200 to 2800. So even with three billion more people, everyone still had more to eat thanks to a production increase of 300% in the same period.

So how much land worldwide was spared in the process thanks to these dramatic yield improvements, for which chemical inputs played a crucial role? The answer is 3 billion hectares, or the equivalent of two South Americas. There would have been no Amazon rainforest left today without this improvement in yields. Nor would there be any tigers in India or orang utans in Indonesia. That is why I don't know why so many of those opposing the use of technology in agriculture call themselves environmentalists.

So where does this opposition come from? There seems to be a widespread assumption that modern technology equals more risk. Actually there are many very natural and organic ways to face illness and early death, as the debacle with Germany's organic beansprouts proved in 2011. This was a public health catastrophe, with the same number of deaths and injuries as were caused by Chernobyl, because E.-coli probably from animal manure infected organic beansprout seeds imported from Egypt.

In total 53 people died and 3,500 suffered serious kidney failure. And why were these consumers choosing organic? Because they thought it was safer and healthier, and they were more scared of entirely trivial risks from highly-regulated chemical pesticides and fertilisers.

If you look at the situation without prejudice, much of the debate, both in terms of anti-biotech and organic, is simply based on the naturalistic fallacy – the belief that natural is good, and artificial is bad. This is a fallacy because there are plenty of entirely natural poisons and ways to die, as the relatives of those who died from E.-coli poisoning would tell you.

For organic, the naturalistic fallacy is elevated into the central guiding principle for an entire movement. This is irrational and we owe it to the Earth and to our children to do better.

This is not to say that organic farming has nothing to offer – there are many good techniques which have been developed, such as intercropping and companion planting, which can be environmentally very effective, even it they do tend to be highly labour-intensive. Principles of agro-ecology such as recyling nutrients and promoting on-farm diversity should also be taken more seriously everywhere.

But organic is in the way of progress when it refuses to allow innovation. Again using GM as the most obvious example, many third-generation GM crops allow us not to use environmentally-damaging chemicals because the genome of the crop in question has been altered so the plant can protect itself from pests. Why is that not organic?

Organic is also in the way when it is used to take away choice from others. One of the commonest arguments against GM is that organic farmers will be ‘contaminated’ with GM pollen, and therefore no-one should be allowed to use it. So the rights of a well-heeled minority, which come down ultimately to a consumer preference based on aesthetics, trump the rights of everyone else to use improved crops which would benefit the environment.

I am all for a world of diversity, but that means one farming system cannot claim to have a monopoly of virtue and aim at excluding all other options. Why can’t we have peaceful co-existence? This is particularly the case when it shackles us to old technologies which have higher inherent risks than the new.

It seems like almost everyone has to pay homage to ‘organic’ and to question this orthodoxy is unthinkable. Well I am here to question it today.

The biggest risk of all is that we do not take advantage of all sorts of opportunities for innovation because of what is in reality little more than blind prejudice. Let me give you two examples, both regrettably involving Greenpeace.

Last year Greenpeace destroyed a GM wheat crop in Australia, for all the traditional reasons, which I am very familiar with having done it myself. This was publicly funded research carried out by the Commonwealth Scientific Research institute, but no matter. They were against it because it was GM and unnatural.

What few people have since heard is that one of the other trials being undertaken, which Greenpeace activists with their strimmers luckily did not manage to destroy, accidentally found a wheat yield increase of an extraordinary 30%. Just think. This knowledge might never have been produced at all, if Greenpeace had succeeded in destroying this innovation. As the president of the NFU Peter Kendall recently suggeseted, this is analogous to burning books in a library before anyone has been able to read them.

The second example comes from China, where Greenpeace managed to trigger a national media panic by claiming that two dozen children had been used as human guinea pigs in a trial of GM golden rice. They gave no consideration to the fact that this rice is healthier, and could save thousands of children from vitamin A deficiency-related blindness and death each year.

What happened was that the three Chinese scientists named in the Greenpeace press release were publicly hounded and have since lost their jobs, and in an autocratic country like China they are at serious personal risk. Internationally because of over-regulation golden rice has already been on the shelf for over a decade, and thanks to the activities of groups like Greenpeace it may never become available to vitamin-deficient poor people.

This to my mind is immoral and inhumane, depriving the needy of something that would help them and their children because of the aesthetic preferences of rich people far away who are in no danger from Vitamin A shortage. Greenpeace is a $100-million a year multinational, and as such it has moral responsibilities just like any other large company.

The fact that golden rice was developed in the public sector and for public benefit cuts no ice with the antis. Take Rothamsted Research, whose director Maurice Moloney is speaking tomorrow. Last year Rothamsted began a trial of an aphid-resistant GM wheat which would need no pesticides to combat this serious pest.

Because it is GM the antis were determined to destroy it. They failed because of the courage of Professor John Pickett and his team, who took to YouTube and the media to tell the important story of why their research mattered and why it should not be trashed. They gathered thousands of signatures on a petition when the antis could only manage a couple of hundred, and the attempted destruction was a damp squib.

One intruder did manage to scale the fence, however, who turned out to be the perfect stereotypical anti-GM protestor – an old Etonian aristocrat whose colourful past makes our Oxford local Marquess of Blandford look like the model of responsible citizenry.

This high-born activist scattered organic wheat seeds around the trial site in what was presumably a symbolic statement of naturalness. Professor Pickett's team tell me they had a very low-tech solution to getting rid of it – they went round with a cordless portable hoover to clear it up.

This year, as well as repeating the wheat trial, Rothamsted is working on an omega 3 oilseed that could replace wild fish in food for farmed salmon. So this could help reduce overfishing by allowing land-based feedstocks to be used in aquaculture. Yes it's GM, so expect the antis to oppose this one too, despite the obvious potential environmental benefits in terms of marine biodiversity.

I don't know about you, but I've had enough. So my conclusion here today is very clear: the GM debate is over. It is finished. We no longer need to discuss whether or not it is safe – over a decade and a half with three trillion GM meals eaten there has never been a single substantiated case of harm. You are more likely to get hit by an asteroid than to get hurt by GM food. More to the point, people have died from choosing organic, but no-one has died from eating GM.

Just as I did 10 years ago, Greenpeace and the Soil Association claim to be guided by consensus science, as on climate change. Yet on GM there is a rock-solid scientific consensus, backed by the American Association for the Advancement of Science, the Royal Society, health institutes and national science academies around the world. Yet this inconvenient truth is ignored because it conflicts with their ideology.

One final example is the sad story of the GM blight-resistant potato. This was being developed by both the Sainsbury Lab and Teagasc, a publicly-funded institute in Ireland – but the Irish Green Party, whose leader often attends this very conference, was so opposed that they even took out a court case against it.

This is despite the fact that the blight-resistant potato would save farmers from doing 15 fungicide sprays per season, that pollen transfer is not an issue because potatoes are clonally propagated and that the offending gene came from a wild relative of the potato.

There would have been a nice historical resonance to having a blight-resistant potato developed in Ireland, given the million or more who died due to the potato famine in the mid 19th century. It would have been a wonderful thing for Ireland to be the country that defeated blight. But thanks to the Irish Green Party, this is not to be.

And unfortunately the antis now have the bureaucrats on their side. Wales and Scotland are officially GM free, taking medieval superstition as a strategic imperative for devolved governments supposedly guided by science.

It is unfortunately much the same in much of Africa and Asia. India has rejected Bt brinjal, even though it would reduce insecticide applications in the field, and residues on the fruit. The government in India is increasingly in thrall to backward-looking ideologues like Vandana Shiva, who idealise pre-industrial village agriculture despite the historical fact that it was an age of repeated famines and structural insecurity.

In Africa, ‘no GM’ is still the motto for many governments. Kenya for example has actually banned GM foods because of the supposed “health risks” despite the fact that they could help reduce the malnutrition that is still rampant in the country – and malnutrition is by the way a proven health risk, with no further evidence needed. In Kenya if you develop a GM crop which has better nutrition or a higher yield to help poorer farmers then you will go to jail for 10 years.

Thus desperately-needed agricultural innovation is being strangled by a suffocating avalanche of regulations which are not based on any rational scientific assessment of risk. The risk today is not that anyone will be harmed by GM food, but that millions will be harmed by not having enough food, because a vocal minority of people in rich countries want their meals to be what they consider natural.

I hope now things are changing. The wonderful Bill and Melinda Gates foundation recently gave $10 million to the John Innes Centre to begin efforts to integrate nitrogen fixing capabilities into major food crops, starting with maize. Yes, Greenpeace, this will be GM. Get over it. If we are going to reduce the global-scale problem of nitrogen pollution then having major crop plants fixing their own nitrogen is a worthy goal.

I know it is politically incorrect to say all this, but we need a a major dose of both international myth-busting and de-regulation. The plant scientists I know hold their heads in their hands when I talk about this with them because governments and so many people have got their sense of risk so utterly wrong, and are foreclosing a vitally necessary technology.

Norman Borlaug is dead now, but I think we honour his memory and his vision when we refuse to give in to politically correct orthodoxies when we know they are incorrect. The stakes are high. If we continue to get this wrong, the life prospects of billions of people will be harmed.

So I challenge all of you today to question your beliefs in this area and to see whether they stand up to rational examination. Always ask for evidence, as the campaigning group Sense About Science advises, and make sure you go beyond the self-referential reports of campaigning NGOs.

But most important of all, farmers should be free to choose what kind of technologies they want to adopt. If you think the old ways are the best, that's fine. You have that right.

What you don't have the right to do is to stand in the way of others who hope and strive for ways of doing things differently, and hopefully better. Farmers who understand the pressures of a growing population and a warming world. Who understand that yields per hectare are the most important environmental metric. And who understand that technology never stops developing, and that even the fridge and the humble potato were new and scary once.

So my message to the anti-GM lobby, from the ranks of the British aristocrats and celebrity chefs to the US foodies to the peasant groups of India is this. You are entitled to your views. But you must know by now that they are not supported by science. We are coming to a crunch point, and for the sake of both people and the planet, now is the time for you to get out of the way and let the rest of us get on with feeding the world sustainably.

Thankyou.

Posted in: agriculture, developing countries, food, genetic engineering

323 comments

Pekka Taipale says:
3 January 2013 at 2:38 pm

Excellent. Thank you.

Reply

Eimhin says:
4 January 2013 at 10:28 pm

Hi, its 15degrees celcius in Ireland today…this time last year the waterfall in town was frozen. Whats a myth? The reduction of tangible reality from matter to form in successive steps of transformation, none of which resemble the former a.k.a, science, or experienced reality?

Now this probably won't get past the moderator, but I want someone to read this, even if only the person who decides my say contradicts their intentional end in publishing this pice of manipulation-in-formation. Certain things are not mythos, look around you, are conditions getting better or worse, try to see beyond yourself, look at the community at large. For whom are things getting better, what is going on in the margins? Our 'progress' is one in which value is reduced, as per the scientific method, to a symbol of that which it represents…and this symbol becomes the object of material greed. Certain things reek of inevitability. Technology by itself is all well and good, but Einstein may have agreed with Leanardo da Vinci's destruction of some of his own inventions as a result of his foresight into the reult of their consequence. Human nature being such as it is, choose wisely. Given the greed of the mass-human, what guarantees can you assure yourself of?

BIOTECHNOLOGY

Drug-making plant blooms

Approval of a 'biologic' manufactured in plant cells may pave the way for similar products.

BY AMY MAXMEN

It was midnight when an anxious Ari Zimran finally got the phone call for which he had been waiting. The news couldn't have been better: the drug he had worked on for nearly a decade had just been approved by the US Food and Drug Administration (FDA).

Zimran, who heads the Gaucher Clinic in Jerusalem and is a member of the scientific advisory board at Protalix Biotherapeutics, a small biotechnology firm in Carmiel, Israel, was not the only one celebrating the company's success last week. Biotechnologists around the world cheered, because Protalix's Elelyso (taliglucerase alfa) is the first biological drug for human use that is manufactured inside modified plant cells.

"It's a great day for plant-made pharmaceuticals," says Scott Deeter, president of Ventria Bioscience, a biotech firm based in Fort Collins, Colorado. "This shows the triumph of innovators over the status quo, and that's really very important."

Drugs that are based on large biological molecules — known as biologics — have been produced inside genetically engineered animal cells, yeast and bacteria for more than two decades. Insulin has been made by genetically modified *Escherichia coli* bacteria since 1982, and by 2010, the global market for such therapies had reached about US$149 billion.

Since the early 1990s, some researchers have been developing plants that could act as cheaper factories for biologics. Plant-cell cultures are also attractive because they require less precise conditions for growth than animal cells. But efforts to exploit plants in this way have lagged, in part because companies and investors were wary of this unfamiliar production method.

Protalix was strategic in targeting a rare heritable disorder called Gaucher's disease, because current means of producing treatments for it have fallen short. The disease is caused by an enzyme malfunction that results in the accumulation of fat in cells and organs, with symptoms ranging from bone deterioration to anaemia. Two existing drugs compensate for the enzyme deficiency, but they can cost up to $300,000 per year in the United States, and drug shortages in recent years have left some patients in need of hospital care.

Structurally, Protalix's Elelyso resembles one of those drugs: Cerezyme, made by Genzyme in Cambridge, Massachusetts. Cerezyme is produced in modified hamster cells, which require regulated temperatures, a complex growth solution and an environment scrubbed free of the viruses that infect hamsters and humans alike. These factors contributed to manufacturing problems that dogged Genzyme last year, limiting supplies of Cerezyme.

> **"It's really the regulatory hurdles and costly clinical trials that are a barrier."**

Protalix's solution is to take a normal version of the human gene affected in Gaucher's disease and introduce it into carrot cells, which are more robust than hamster cells, and then extract the enzyme they make. The lower production overheads will allow the company to sell Elelyso for just 75% of the price of Cerezyme, the most popular drug on the market, says David Aviezer, Protalix's president.

Charles Arntzen, a plant biotechnologist at Arizona State University in Tempe, says that Elelyso's approval sends a clear and positive signal to investors and companies that plant-manufactured drugs are worth pursuing (see 'Plants in the pipeline'). When he began working on plant-made vaccines in 1991, he says that he was naive about how long it would take for the technology to blossom. He expected companies and the FDA to embrace the technique, speeding inexpensive products to market.

"Many of us in academia thought that manufacturing costs were a significant part of the entry barrier in making a new product," Arntzen says. But "it's really the regulatory hurdles and costly clinical trials that are a barrier, and big pharmaceutical companies don't want to take this on because they know there is an enormous risk inherent to trying something new".

For those companies trying to produce drugs from whole plants, rather than in cultures of plant cells, Aviezer cautions that Elelyso's approval might not set a precedent. But others in the field are more optimistic. "Even though [Protalix's] technology doesn't use whole plants, it does address many issues of producing proteins in plant cells," says molecular immunologist Julian Ma of St George's, University of London, who is scientific coordinator for Pharma-Planta, a European consortium that is developing plant-derived pharmaceuticals to treat, for example, HIV (see *Nature* **458,** 951; 2009).

Nathalie Charland of Canadian biotech company Medicago, in Quebec City, which is developing vaccines produced in tobacco plants, agrees: "I don't think there will be major differences in how the FDA handles their product and ours." ■

PLANTS IN THE PIPELINE

Manufacturers have begun or completed phase II clinical trials on a handful of biologics made in plants, and hope to follow Elelyso to market.

Drug	Condition	Company	Platform
Locteron (interferon-α)	Hepatitis C	Biolex Therapeutics	Duckweed
H5N1 vaccine	Influenza	Medicago	Tobacco
VEN100	Antibiotic-associated diarrhoea	Ventria Bioscience	Rice
CaroRx	Dental caries	Planet Biotechnology	Tobacco

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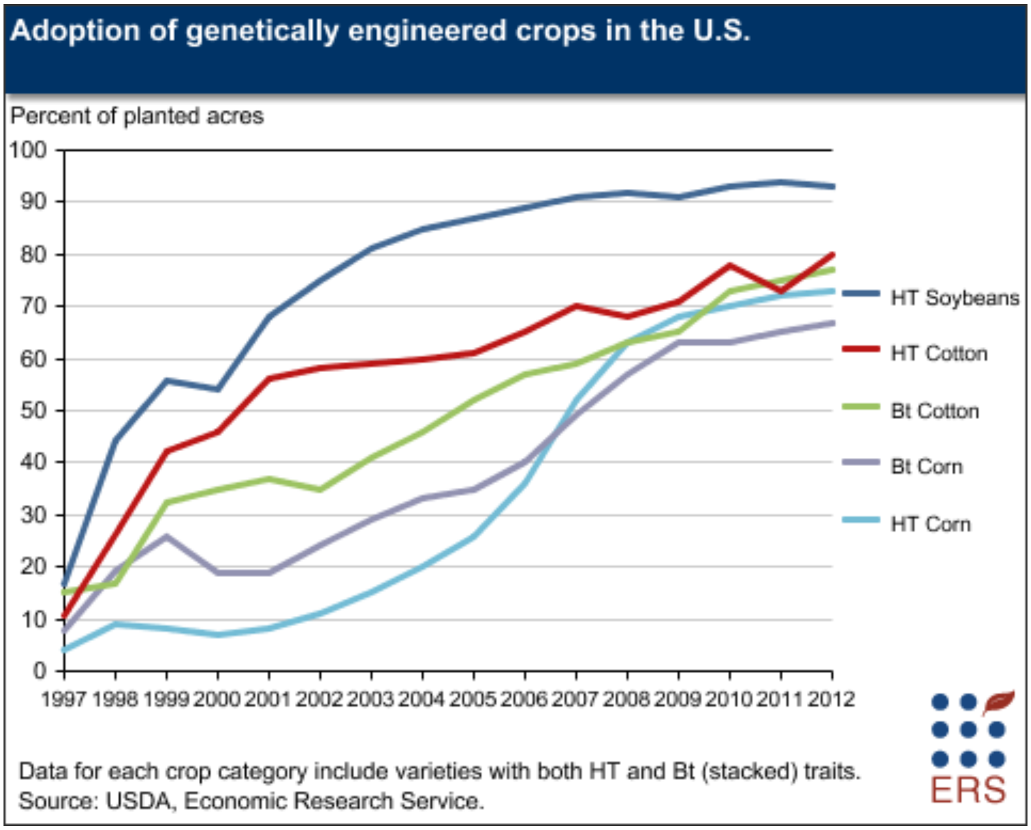
CORRECTION

The News Feature 'Date with history' (*Nature* **485,** 27–29; 2012) incorrectly located the University of Waikato in Wellington instead of Hamilton.

Economic Research Service

United States Department of Agriculture



Adoption of genetically engineered crops in the U.S.

Data for each crop category include varieties with both HT and Bt (stacked) traits.
Source: USDA, Economic Research Service.

chart data

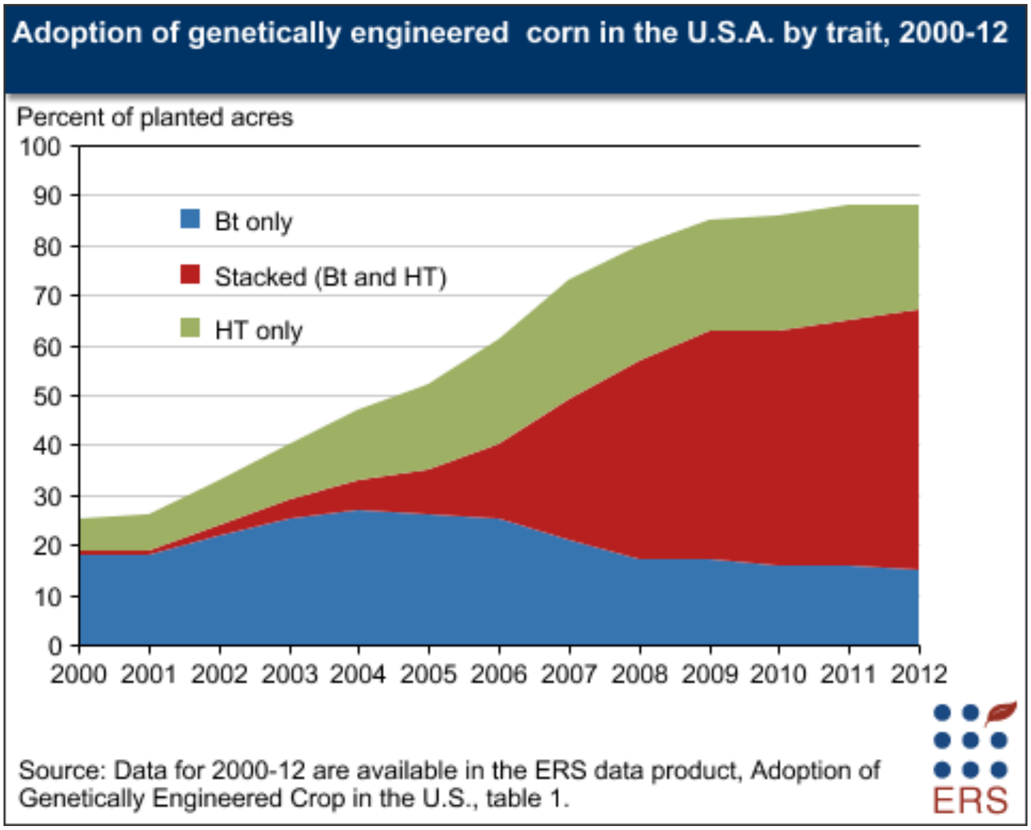
Herbicide-tolerant (HT) crops, developed to survive application of specific herbicides that previously would have destroyed the crop along with the targeted weeds, provide farmers with a broader variety of options for effective weed control. Based on USDA survey data, HT soybeans went from 17 percent of U.S. soybean acreage in 1997 to 68 percent in 2001 and 93 percent in 2012. Plantings of HT cotton expanded from about 10 percent of U.S. acreage in 1997 to 56 percent in 2001 and 80 percent in 2012. The adoption of HT corn, which had been slower in previous years, has accelerated, reaching 73 percent of U.S. corn acreage in 2012.

Insect-resistant crops containing the gene from the soil bacterium Bt (Bacillus thuringiensis) have been available for corn and cotton since 1996. These bacteria produce a protein that is toxic to specific insects, protecting the plant over its entire life. Plantings of Bt corn grew from about 8 percent of U.S. corn acreage in 1997 to 26 percent in 1999, then fell to 19 percent in 2000 and 2001, before climbing to 29 percent in 2003 and 67 percent in 2012. The increases in acreage share in recent years may be largely due to the commercial introduction in 2003/04 of a new Bt corn variety that is resistant to the corn rootworm, a pest that may be more destructive to corn yield than the European corn borer, which was previously the only pest targeted by Bt corn. Plantings of Bt cotton expanded more rapidly, from 15 percent of U.S. cotton acreage in 1997 to 37 percent in 2001 and 77 percent in 2012.

Use of Bt corn will likely continue to fluctuate over time, based on expected infestation levels of European corn borer (ECB), and the corn rootworm which are the main pests targeted by Bt corn. Similarly, adoption of Bt cotton depends on the expected infestation of Bt target pests, such as the tobacco budworm, the bollworm, and the pink bollworm. Adoption appears to have reached the low-growth phase, as adoption has already occurred on acreage where Bt protection is needed most. Insects have not posed major problems for soybeans, so insect-resistant varieties have not been developed.

These figures include adoption of "stacked" varieties of cotton and corn, which have both HT and Bt traits. Adoption of stacked varieties has accelerated in recent years. Stacked cotton reached 63 percent of cotton plantings in 2012. Plantings of stacked corn made up 52 percent of corn acres in 2012.

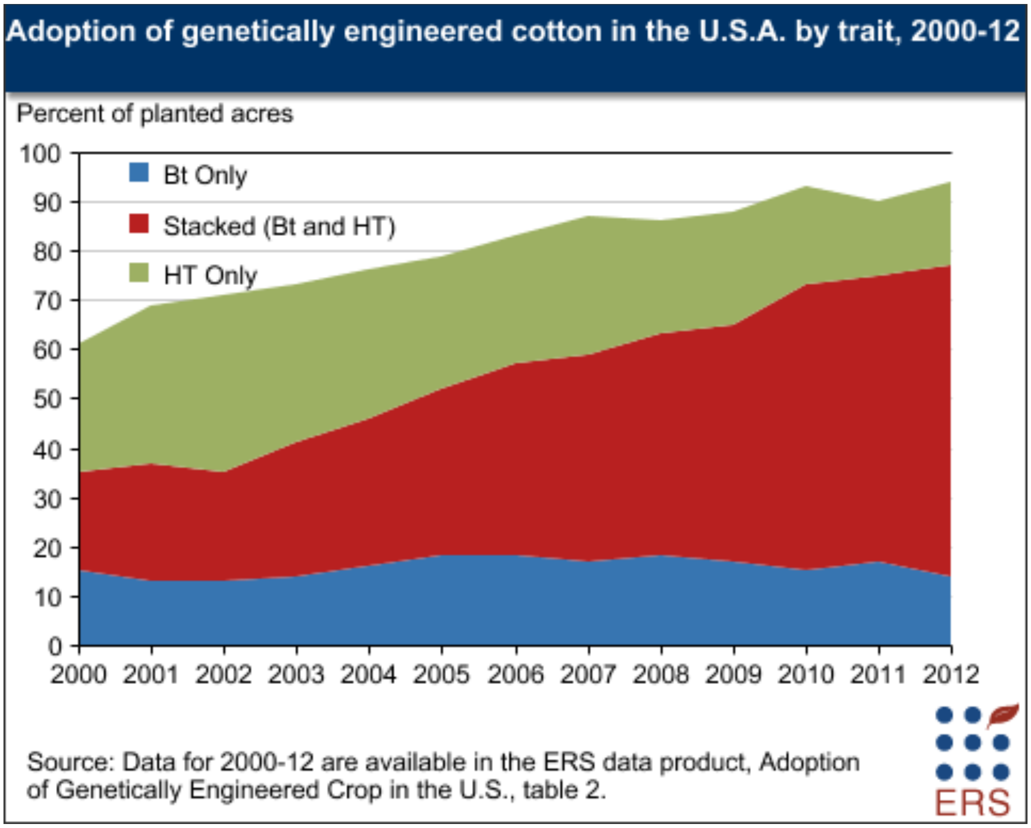
Adoption of all GE cotton, taking into account the acreage with either or both HT and Bt traits, reached 94 percent of cotton acreage in 2012, versus 93 percent for soybeans (soybeans have only HT varieties). Adoption of all biotech corn accounted for 88 percent of corn acreage in 2012.



Adoption of genetically engineered corn in the U.S.A. by trait, 2000-12

Source: Data for 2000-12 are available in the ERS data product, Adoption of Genetically Engineered Crop in the U.S., table 1.

chart data


Adoption of genetically engineered cotton in the U.S.A. by trait, 2000-12

Source: Data for 2000-12 are available in the ERS data product, Adoption of Genetically Engineered Crop in the U.S., table 2.

chart data