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

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.

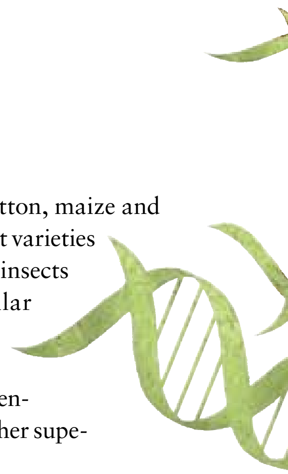
—The Editors

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

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-

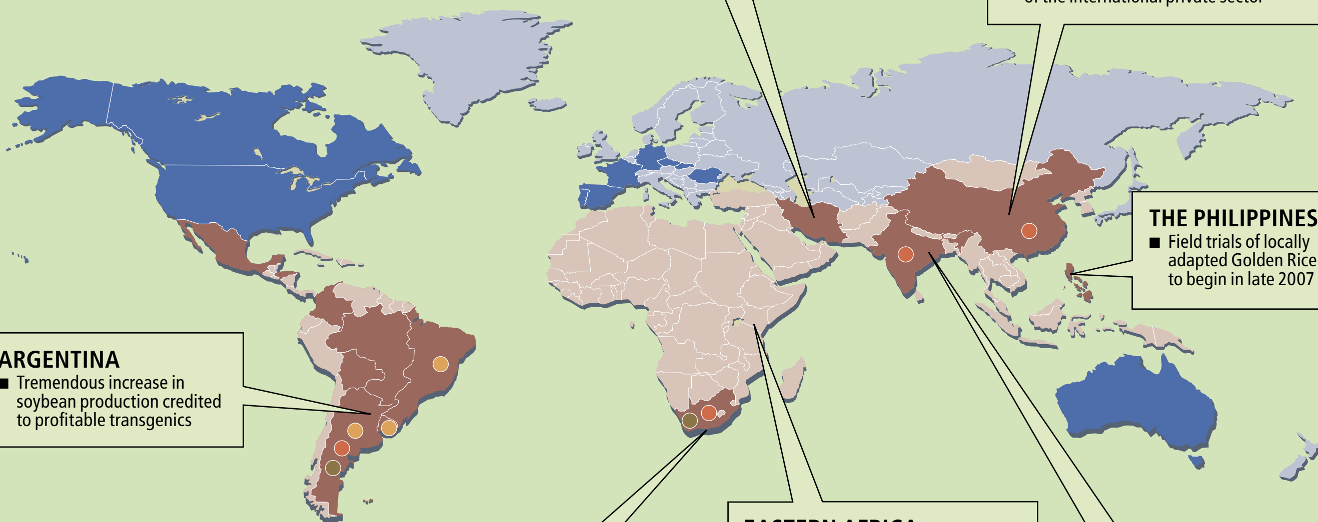
[THE STATUS QUO]

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

EASTERN AFRICA
- Maize streak virus is endemic

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

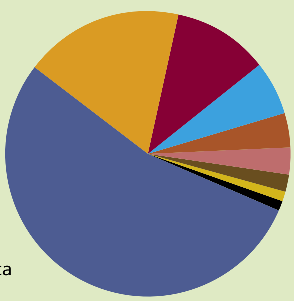
BANGLADESH, CHINA, INDIA, INDONESIA, THE PHILIPPINES, SOUTH AFRICA, VIETNAM
- Research institutes are working with Syngenta to develop locally adapted varieties of Golden Rice

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

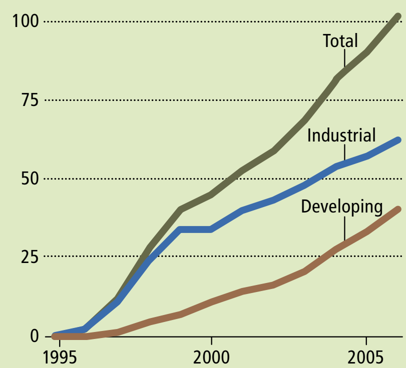
Most transgenic crop plantings are in the U.S. (*below left*), but since 2000, plantings have increased faster in developing nations than in industrial ones (*below middle*). A small number of crops and kinds of modification account for almost all the production (*right*).

THE BIG GROWERS
Transgenic crop area by country (2006)

- **54%** U.S.
- **18%** Argentina
- **11%** Brazil
- **6%** Canada
- **4%** India
- **3%** China
- **2%** Paraguay
- **1%** South Africa
- **1%** Others



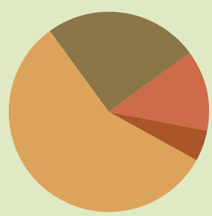
RAPID INCREASES IN TRANSGENICS
Millions of hectares planted



KINDS OF PLANTINGS (2006)

Crops

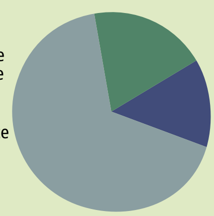
- **57%** Soybean
- **25%** Maize
- **13%** Cotton
- **5%** Canola



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

Traits

- **68%** Herbicide tolerance
- **19%** Insect resistance
- **13%** Both



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.

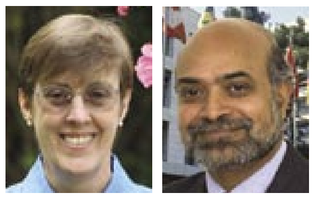
Very few major public- or private-sector programs are targeting crops and animals that the poor rely on or the particular problems that they face. Traits of special interest to the developing world include nutritional enhancement and resistance to production stresses such as drought, salinity, disease 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,

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

[THE AUTHORS]



Terri Raney is senior economist in the Agricultural and Development Economics division of the United Nations Food and Agriculture Organization (FAO) in Rome and chief editor of *The State of Food and Agriculture,* the annual flagship publication of the FAO. Raney grew up on a small farm in Oklahoma and earned a Ph.D. in agricultural economics from Oklahoma State University. She lives with her husband on an olive farm in the Sabine Hills outside of Rome. Prabhu Pingali is director of the Agricultural and Development Economics division of the FAO. Originally from Hyderabad, India, he received a Ph.D. in economics from North Carolina State University and is an internationally recognized expert on the green revolution and technological change in agriculture. Earlier this year he was elected to the U.S. National Academy of Sciences as a foreign associate.

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

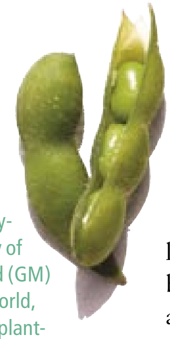
The ultimate success or failure of transgenic crops will depend on whether farmers gain economic benefits from using them. Even when the private-sector research is well suited to conditions in a developing country, access to the technology may be expensive. The contrasting cases of insect-resistant Bt 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.

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-

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.

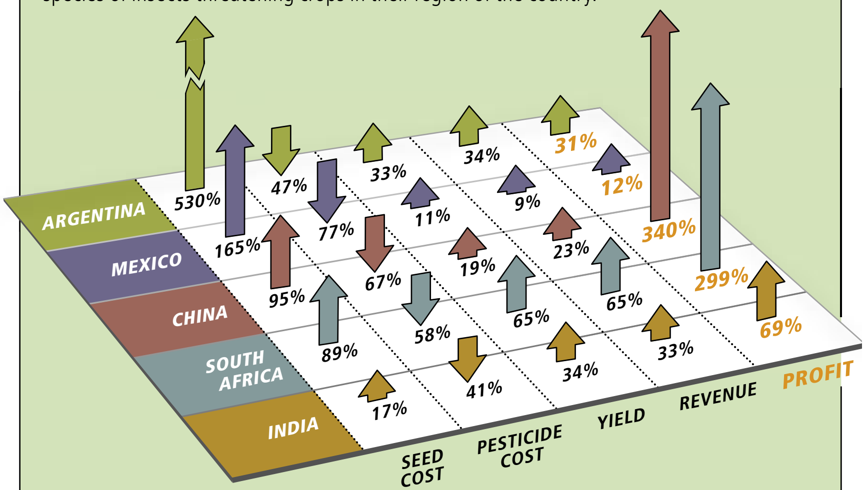
Orphan crops—regional staple foods such as sorghum, pearl millet and pigeon pea—are being neglected by both biotechnology and conventional agricultural research programs.

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

[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.

ANDREW WINNING *Reuters*

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: **www.SciAm.com/ontheweb**

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. ■

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.

Economic Impact of Transgenic Crops in Developing Countries. Terri Raney in *Current Opinion in Biotechnology,* Vol. 17, No. 2, pages 174–178; April 2006.