Opportunities for and Challenges to Plant Biotechnology Adoption in Developing Countries

Gary Toenniessen
Rockefeller Foundation
New York, NY

The theme of this conference, *Biotechnology: Science and Society at a Crossroad*, is particularly relevant to developing countries, where decisions concerning the use of agricultural technologies profoundly affect large numbers of people. Currently, 80% of the world's population lives in developing countries. By 2050, the United Nations estimates that the global population will increase by roughly 3 billion. This population increase will occur primarily in developing countries, with 90% of the total then living in areas now classified as less developed (United Nations, 2002).

Over the past 50 years, there have been substantial increases in food production and reduction in poverty in the developing world. Despite these favorable trends, the biggest health problem in developing countries remains malnourishment. About 800 million people still consume less than 2,000 calories a day, and are chronically undernourished (FAO, 2002a). A recent analysis indicates that 127 million pre-school children suffer from vitamin-A deficiency, which can cause blindness and early death (West, 2002). Iron deficiency is common, with about 400 million women of childbearing age afflicted by anemia. As a result, they give birth to underweight children and are more likely to die in childbirth. Roughly 24,000 people die each day from hunger and hunger-related causes, three-quarters of them children.

While many correctly argue that the root cause of such hunger is poverty, some seem to miss that, in predominantly agrarian societies, the root cause of poverty is lack of sufficient food and income from small-scale farming. China and India each has over 500 million people living on small-scale farms. Sub-Saharan Africa has over 400 million and this number is increasing rapidly, despite rapid urbanization (FAO, 2002b). In the poorest countries, like Malawi, over 90% of the population depend on small-scale farming for their livelihoods. It is in rural areas of such countries that the most severe poverty occurs. In Asia and Africa, over 75% of one billion people living in extreme poverty, earning less than a dollar a day, live in rural areas, and are dependent on agriculture for their meager incomes (World Bank, 2003). They are often hindered by traditional farming methods, increasingly depleted soils, shrinking plots of land, scarce and unreliable water, inequitable land-distribution patterns, and inefficient or unfair markets. Yet they have few, if any, good non-agriculture-dependent livelihood options.

Clearly, these small-scale farmers and their governments should have the major say in deciding which roads to take in promoting further agricultural development and food security for all. Unfortunately—at least with regard to agricultural biotechnology—this is not likely to be the case. Rather, decisions are being made now in industrialized countries and in global fora dominated by rich countries that will significantly influence the choices available to developing countries. As these decisions are made, we should at least try to give greater consideration and greater voice to the billions of small-scale farmers these decisions will most seriously affect.

AN INTEGRATED APPROACH

The questions for this conference thus become:

- What opportunities exist for biotechnology to contribute toward improving agricultural productivity, expanding markets, and stimulating employment and income generation in developing countries?
- What are the risks associated with using biotechnology in developing countries?
- What challenges do these countries face in realizing the more promising of these opportunities and in mitigating the risks?

Agricultural biotechnology is clearly not *the* solution to poverty and hunger. Rather, it is simply a set of powerful new tools that can facilitate the production, multiplication, and distribution of improved crop varieties. Improved crop varieties, in turn, represent just one of the contributions that science and technology can make to agricultural development. Equally important are agro-ecological research, agronomic research, enhanced soil fertility, integrated pest management, water-resource management, and integration of crops and livestock. Farmer-participatory research draws on indigenous knowledge and allows all technologies to be brought together in ways that are synergistic and improve the productivity and profitability of the farm.

Just as important as inputs from science and technology are roads, credit, extension, access to fertilizer, input and output markets, land reform, institutions that effectively serve smallholder farmers, and policies that favor, or at least do not penalize, them. Where these factors come together in the same place, at the same time, as they have in large parts of Asia, they provide greater food security and economic growth through small-scale agriculture. These generate greater income that is often used for health care and education. Better educated, healthier and wealthier farm families, in turn, contribute to further agricultural development, to off-farm economic activities, and to overall national economic growth (Delgado *et al.*, 1998). Biotechnology can make an important contribution to this economic development process as a component of a crop-improvement program that is a component of a broader agricultural development program.

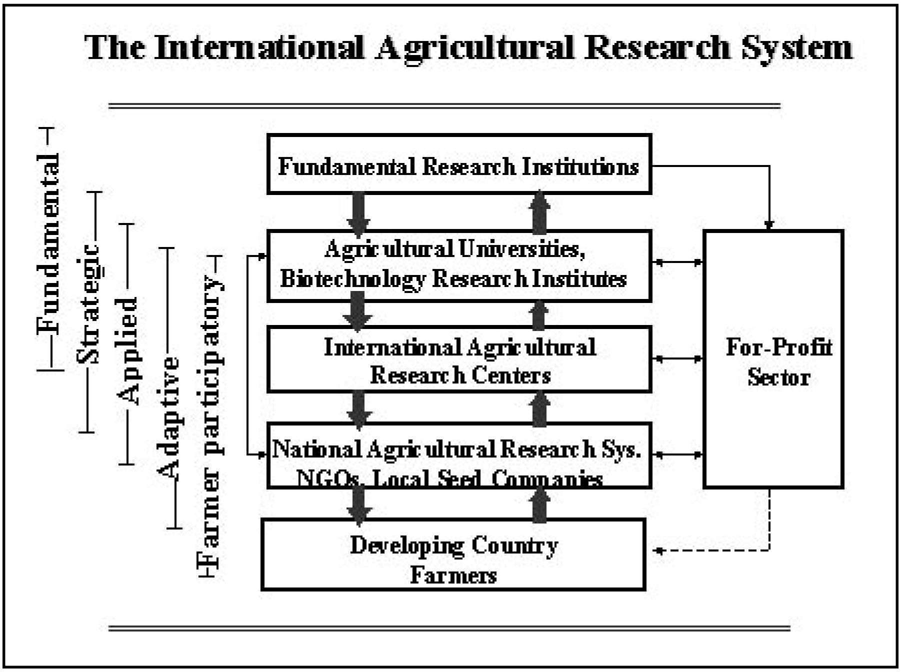

Figure 1. The international agricultural research system.

THE INTERNATIONAL AGRICULTURAL RESEARCH SYSTEM

Fortunately, in agriculture, the public sector has traditionally played an important role both in research and in the production of end products that address the needs of the poor and hungry. Agricultural universities, agricultural research agencies and extension services have been established in most countries and charged with developing and delivering new technologies to farmers, usually in the form of better seed and improved agronomic practices. The international agricultural research system, depicted in Figure 1, was established in the 1960s and 1970s, specifically to develop better crop varieties and improved farming methods for smallholder farmers in developing countries.

Sixteen international agricultural research centers (*e.g.*, the International Maize and Wheat Improvement Center based in Mexico, the International Rice Research Institute based in the Philippines, and the International Institute for Tropical Agriculture based in Nigeria), play a central role by producing breeding lines and other "global public goods" that are made freely available to everyone.

Interestingly, our host institution, Washington State University, was directly involved in one of the early and most important accomplishments of this international system. In the 1950s, Orville Vogel, the legendary USDA wheat breeder at Washington State, had obtained a dwarf variety of wheat from Japan. He crossed it with North American wheat to produce the first semi-dwarf winter-habitat varieties that had higher yield potential. They were rapidly adopted in the United States. But long before he had released any semi-dwarfs, Dr. Vogel shared a few of his early-generation seeds with Norman Borlaug in Mexico. There, through much breeding effort, the semi-dwarf trait was transferred to the local spring-habitat wheat varieties. The first Mexican semi-dwarfs were released in 1962. Shortly thereafter, they were shared with India and Pakistan, where they performed surprisingly well, and the Green Revolution in Asia was under way (Hanson *et al.*, 1982). Today, the vast majority of improved varieties of staple food crops grown in developing countries are the product of such public-sector international agricultural research collaborations.

Evenson and Gollin (2003) recently summarized an extensive review of the outputs and impacts of this international network. They examined the development and adoption in developing countries of modern varieties of eleven crops over the period 1960 to 2000. As in the case of wheat, many of these varieties employed dwarfing genes that gave them shorter, stiffer stems, channeled greater photosynthate into grain, and made them more responsive to fertilizer. From 1960 to 2000, over 400 public breeding programs in over 100 countries released over 8,000 modern varieties of the eleven crops. Greater than 35% of these varieties were based on crosses made at international centers. Even most of the hybrid maize, sorghum, and millet marketed by local seed companies in developing countries were based on "platform" varieties generated by these public-sector breeding programs.

TABLE 1. INCREASES IN YIELDS IN DEVELOPING COUNTRIES, 1962 TO 2002 (FAO, 2002B).

Crop	1962 (t/ha)	2002 (t/ha)	Increase (%)
Wheat	0.9	2.7	200
Rice	1.8	3.9	117
Maize	1.2	3.0	150
Sorghum	0.7	1.1	57
Potato	8.6	15.2	77
Cassava	7.5	10.7	43

Table 1 summarizes the yield increases in developing countries that have occurred for several crops over the past 40 years. For rice, maize, and wheat, which together provide more than half of the food energy consumed in developing countries, average yields have more than doubled. With increased production, food prices dropped, average caloric intake rose and there were corresponding gains in health and life expectancy. In Asia, the proportion of the population suffering from chronic hunger dropped from 40% to 20% while the overall population more than doubled.

However, adoption of the modern varieties and benefits derived from them were not evenly distributed. They performed best with an adequate supply of water and fertilization. In Asia and Latin America, poor urban consumers, who spend a large proportion of their income on food, clearly benefited from lower prices. Farmers whose productivity rose more than prices fell gained additional income. As a result, large regions of Asia experienced economic growth. Some farmers who produce most of their own food and sell little, benefited from increased productivity. Some farmers who buy most of their food and sell cash crops benefited from lower food prices. But farmers who primarily grow and sell staple food crops, and who had limited productivity gains while food prices fell, benefited little and in some cases suffered economic losses. A key goal of biotechnology should be to help those farmers who gained little from the Green Revolution.

In sub-Saharan Africa, there were only minimal increases in yields, yet significant increases in production still occurred. This was achieved by extending the area under cultivation and mining the soil of plant nutrients through shorter fallow periods. But production has not kept pace with population growth in Africa, and a decade-long drop in per-capita food production continues. Today, Africa faces a food crisis and an environmental crisis, both resulting from low-input, low-yield agriculture.

The small-scale farmers in Africa and in other regions, who benefited little from past innovations, need what Gordon Conway has coined a "Doubly Green Revolution" (Conway, 1999): a scientific revolution that helps farming families over a broad range of agro-ecosystems achieve sustainable advances in productivity and profitability per unit of land, labor, and capital, while restoring the long-term productivity of their farms. Such new agricultural technologies should focus on foods consumed by the poor, be scale-neutral, minimize external inputs, maximize inputs internal to the farm, focus on traits important to poor farmers (*e.g.*, stress resistance), benefit mixed cropping systems, and enhance human nutrition. This will require an approach that employs exciting new farmer-participatory methods, draws on the best of agro-ecological research combined with judicious use of fertilizer to help restore soil fertility, and crop genetic improvement achieved through conventional plant breeding and biotechnology (DeVries and Toenniessen, 2001).

OPPORTUNITIES FOR BIOTECHNOLOGY

With regard to crop biotechnology, three forms of its application are now benefiting poor farmers:

- tissue culture, based primarily on advances in plant cellular biology,
- marker-aided selection, based on our ability to analyze plant and plant-pathogen DNA and detect the presence or absence of particular DNA sequences, and
- genetic engineering, based on recombinant-DNA technology and the ability to incorporate new genes into plant chromosomes.

Genomics and related methods in bio-informatics are a fourth type of technology currently generating vast quantities of data, but still at an uncertain early stage of application.

Tissue Culture

Protocols for regenerating whole plants from single cells or clumps of cells were first generated over three decades ago. Today, these protocols form the basis of micro-propagation technologies that are relatively simple and widely used in horticulture and with ornamental and other crops. Used properly under sterile conditions, these techniques have the added advantage of excluding nearly all diseases from the regenerated plantlets. Profitable new industries based on such micro-propagation have been established in Asia and Latin America, and increasingly in Africa. Tissue culture greatly speeds up the dissemination of improved varieties of crops such as cassava, sweet potato, and banana that have low multiplication ratios under traditional vegetative propagation. In the East African highlands, where banana is a staple crop, micro-propagation of improved and disease-free seedlings is becoming a small-scale business that is improving food production and generating increased income for small-scale farmers and rural laborers involved in production and distribution both of the seedlings and the banana harvest (Wambugu & Kioime, 2001.)

Anther culture is a special form of tissue culture that can speed breeding. It has already contributed to the production of new rice varieties that are spreading rapidly in developing countries. Anther culture results in homozygous doubled haploid lines of use to breeders in making predictive crosses and for the production of true-breeding varieties, so farmers can save a portion of their harvest as seed for subsequent plantings.

In Asia and Africa, anther culture is being used to produce promising new varieties resulting from crossing different species of rice. If different species are forced to cross by breeders, they produce progeny with low fertility and low yields, due to poor chromosome pairing. However, when such progeny plants are passed through anther culture, the regenerated plants have perfectly paired chromosomes and are fertile, yet contain DNA (and genetic traits) derived from both parents of the original cross. At the West Africa Rice Development Association (WARDA) in Côte d'Ivoire, anther culture is being used to combine the best traits of Asian rice (*Oryza sativa*), such as high-yield potential, with the best traits of African rice (*Oryza glaberrima*), such as early maturity, weed competitiveness and drought tolerance (Jones, 1999). By using anther culture to produce thousands of lines with different combinations of traits derived from Asian and African cultivars, WARDA has been able to identify over a dozen highly promising lines, which farmers then evaluate through participatory varietal selection. The first of these "New Rices for Africa" (NERICAs) are now being grown by over 20,000 upland farmers in Guinea, where they are more than doubling yields. These rices could well be the beginning of a Doubly Green Revolution for Africa, achieved through new methods of participatory plant breeding, biotechnology, and integrated nutrient management.

Current research on anther culture of cassava is aimed at generating in-bred lines for crossing to produce advanced hybrid varieties. This could lead to yield increases from hybrid cassava similar to the major advances that occurred with hybrid maize. In the case of cassava, such hybrid varieties would most likely be disseminated to national programs as "clean" true seed and then disseminated to farmers as cuttings.

Marker-Aided Selection

This technology is based on the ability of laboratory scientists to detect specific sequences of DNA at specific locations on the chromosomes of an organism. For plant-breeding purposes, a useful DNA marker is one that is easily detectable, is genetically linked to one or more useful traits, and generates some reproducibly different signals (usually different band positions on a gel) for each of the two parent plants used in a cross. Using such markers, breeders can determine the inheritance of linked traits in progeny at the seed or seedling stage even if the trait is expressed only in the mature plant. Marker-aided selection (MAS) is particularly useful for traits like root depth and vigor that are difficult and/or expensive to score using phenotypic screening.

MAS has multiple applications in crop improvement, but, to date, has proved most useful as a tool to speed backcrossing of qualitative traits such as many forms of disease resistance. With marker-aided backcrossing, a desired trait can be moved to a superior variety in four to six generations rather than ten or more required without markers. For example, in January 2002, the government of Indonesia released two new rice varieties, 'Angke' and 'Conde,' which were derived by disease-resistance breeding augmented with MAS to pyramid bacterial blight resistance genes into commercially adapted varieties (Bustamam *et al.*, 2002).

MAS holds great promise also in breeding for complex quantitative (multi-gene) traits like drought tolerance. To achieve a desired quantitative trait, the genes controlling the trait, termed quantitative trait loci (QTLs) must be present in their most favorable format. By mapping these loci and using their markers to track their occurrence in large numbers of genotypes, it is possible to identify the markers associated with plants that have the most favorable genetic make up. The right combination of QTLs can then be duplicated in a breeding program using the markers.

Currently, many research groups worldwide are attempting to demonstrate the success of MAS in breeding for drought tolerance in cereal crops. A key challenge faced by these groups is determination of genomic regions (*i.e.*, QTLs) that enhance performance across varying combinations of water-stress conditions, growth stages and environments. Ribaut *et al.* (2002) examined the genetic control of the drought tolerance that has been successfully introduced into maize varieties in southern Africa. They focused on the molecular-genetic dissection of component traits that are associated with this tolerance, and identified QTLs that are associated with components-of-yield of crops under drought stress.

Recent approaches for improving drought tolerance in pearl millet have focused on the development of QTL molecular markers for drought tolerance during the vulnerable flowering and grain-filling stages (Yadav *et al.*, 2002). One QTL, which explained 23% of yield under water deficits, was common across environments and has been integrated into pearl millet breeding programs using markers. In sorghum, drought that occurs after flowering is particularly detrimental to yields, and the "stay-green" trait (*i.e.*, delayed leaf senescence) has been associated with greater drought tolerance. Sanchez *et al.* (2002) reviewed the mapping of "stay-green" QTLs for drought tolerance and reported that four are consistently associated with the trait in field experiments and explain 53% of the phenotypic variation.

Genetic Engineering

This is a collection of techniques that enable scientists to move genes from one organism to another including between species. It is the most controversial of the agricultural biotechnologies, in part because it is new and viewed by some as somehow "unnatural," and because—as with all new technologies—there is no way to know the long-term impacts. However, as reported by James (2002), since 1996 there has been a steady increase in the worldwide area planted to transgenic crops with 58.7 million hectares (145 million acres) harvested in sixteen countries in 2002. Roughly six million farmers worldwide grew transgenic crops in 2002, 90% of whom are small-scale growers in developing countries, mostly China.

Genetic engineering is most commonly employed as a means of introducing a new trait when naturally occurring variation is absent or insufficient within the target species. A good example is golden rice: lines that are engineered to synthesize provitamin A (β-carotene) in the endosperm. As reported by Beyer *et al.* (2002), further advances have occurred in the development of golden rice, with mannose now used as a selective agent so that new lines contain no antibiotic resistance. Synthesis of β-carotene is now achieved by adding only two genes, daffodil phytoene synthase (*psy*) and bacterial phytoene desaturase (*crt*I), with rice-endosperm-specific promoters. These new "clean" lines are being crossed by breeders at IRRI and other institutions in Asia with local varieties that are well adapted to regions where vitamin-A deficiency is prevalent.

Another well known example is resistance to chewing and boring insects, which is lacking in many crops. Such resistance has been engineered into several crops with gene constructs derived from the bacterium *Bacillus thuringiensis* (*Bt*) that encode proteins that disrupt the digestive system of specific insect pests.

Transgenic cotton varieties containing *Bt* genes are now grown commercially in China, South Africa, Mexico, Argentina, Indonesia, and India. Pray *et al.* (2002) have followed the adoption of *Bt* cotton in China, which began in 1977. By 2001, 3.5 million Chinese farmers, growing on average 0.42 hectares, planted 1.5 million hectares of *Bt* cotton, roughly 31% of the area planted to cotton in China. More farmers are now benefiting from *Bt* cotton in China than there are farmers in the United States. The rapid spread of *Bt* cotton was driven by farmers' demands for a technology that increases yield, reduces insecticide use and costs, reduces insecticide poisonings and requires less labor. Initial yield increases were in the 5 to 10% range and modest increases continue, suggesting that farmers are learning to manage *Bt* varieties better. There is no indication that insect pests are becoming resistant to *Bt* cotton. The use of insecticides in China has been reduced substantially due to *Bt* cotton. The use of formulated insecticide fell by 20,000 tons in 1999 and by 78,000 tons in 2001, the latter being roughly a quarter of all of the insecticide sprayed in

China before the adoption of *Bt* cotton. Cost savings for farmers are now beginning to push down the price of cotton, so consumers will also benefit. *Bt* technology is being used increasingly in China as a component of integrated pest management strategies.

The Beijing-based Biotechnology Research Institute of the Chinese Academy of Agricultural Sciences originally developed many of the *Bt* cotton varieties (Fang *et al.*, 2001). In fact, in China, public-sector institutions have produced and field-tested transgenic varieties of over fifteen different species, including many minor crops (FAO, 2003).

Public research institutions in countries such as China, India, and Brazil, which have both excellent scientific capacity and greater "freedom-to-operate," are likely to become the primary employers of plant biotechnology to deliver useful new varieties of tropical crops to farmers with limited purchasing power. The private sector is increasingly concentrating on only a handful of major crops and profitable markets. And, owing to proprietary property and regulatory constraints, public-sector institutions in industrialized countries find it increasingly difficult to commercialize products of plant biotechnology without corporate sponsors.

CHALLENGES

Proprietary Property

The genetic improvement of plants is a process in which each enhancement is based directly on preceding generations and requires the physical use of the material itself. Most of the important food crops originated in what are now developing countries, and much of the value in today's seeds has been added over the centuries, as farmers selected their best plants as a source of seed for their next planting. Traditionally, these land races and the indigenous farmer knowledge associated with them were free of charge to collectors and, hence, to the world community. In exchange, public-sector research and breeding programs, like those of Drs. Vogel and Borlaug, added valuable traits and returned scientific knowledge and improved breeding lines as "global public goods" to developing and developed countries alike.

However, the rules of the game are changing.

Over the past decade, in industrial countries, applied crop-biotechnology research and the production of improved varieties have increasingly become functions of the "for-profit" private sector (Barton and Berger, 2001). This has led to a significant increase in the total plant-science and crop-improvement research, but the results of such research are generally protected by intellectual property rights (IPR) of various forms, including patents, material-transfer agreements, plant breeders' rights, and trade secrets. Increasingly, this is true of results from public-sector research as well.

Industrial countries have made IPR an important component of international trade negotiations, using them to exploit their competitive advantage in research and development. Countries joining the World Trade Organization, for example, must have IPR systems that include protection of crop varieties, according to the Trade Related Aspects of Intellectual Property Rights (TRIPS) provisions. The least-developed countries have until January 1, 2006, to implement such IPR systems.

Because poor farmers cannot afford to purchase new seed for each planting, it is important that developing-country IPR laws are modeled on plant-variety-protection systems that include provisions allowing farmers to save and replant seed and plant breeders to use varieties for further breeding. This is in contrast to the utility patent system that extends protection to the seed and progeny of patented plants so breeders cannot legally use protected varieties as breeding material.

Ironically, a major IPR change that is threatening the operations of the international agricultural research system comes from public, not private-sector, research institutions. To promote technology transfer and product development in the United States, the 1980 Bayh-Dole Act gave universities and other public-funded research institutions the right to obtain patents on, and commercialize, inventions made under government research grants. Similar arrangements have emerged in Europe, Japan, Australia, and most other industrialized countries. The result is that, while many biotechnology discoveries (*e.g.*, pathogen-derived plant resistance to virus infection) and enabling technologies (*e.g.*, *Agrobacterium* and biolistic transformation methods) are still generated with public funding in research institutions and agricultural universities, these discoveries are no longer being treated as “public goods.” Rather, they are being patented and licensed, often exclusively, to the for-profit sector. Such discoveries now primarily flow from the public sector to the for-profit sector and, if they flow back out, usually come under material-transfer agreements (MTAs) that significantly restrict their use, usually for research purposes only, and often include reach-through provisions to capture results of future research.

Since crop genetic improvement is a derivative process, each increment made through biotechnology now comes with a number of IP constraints, with new IP added with each transfer or further improvement. To deal with this predicament, the private sector is becoming greatly centralized through mergers and acquisitions into a global oligopoly dominated by five firms that are also the major marketers of pesticides. These mergers were made in part to accumulate the IP portfolios necessary to produce biotechnology-derived finished crop varieties with “freedom to operate” and, in part, to gain control over a new technology that is threatening their pesticide markets.

The publicly funded agricultural research community, for the most part, lacks “freedom to operate.” Leading academic researchers are primarily interested in research competitiveness. They readily sign research MTAs to gain access to the latest tools, but are then restricted from further transferring their research products. Many universities now have technology-transfer offices where maximizing licensing and royalty income is just as important as technology transfer, and often achieved by granting exclusive licenses. The net result is that improved plant materials produced by academics are highly IP-encumbered and commercially useful only to companies having an IP portfolio covering most of the technologies used. Golden rice is a well documented example: some forty patents and six MTAs were potential constraints to its dissemination (Kryder *et al.*, 2000).

The international agricultural research system does not have a significant IP portfolio and, as a consequence, the traditional flow of materials through the system is breaking down, particularly where useful new technologies and improved plant materials had flowed from public-sector researchers in developed countries to international centers and national crop-improvement programs in developing countries. Africa, in particular, is being short-changed of the benefits of biotechnology because, unlike Asia and Latin America, its public sector has little capacity to use biotechnology for the benefit of poor farmers, even in countries where the IP is not protected. Africa is much more dependent on partnering with others, but publicly funded researchers in industrial countries are no longer partners who can freely share their most important discoveries and products.

New mechanisms are needed to re-establish and re-invigorate the linkages between universities and the international agricultural research system, and to build new linkages to the expertise and resources of the private sector.

Progress is being made. In the public sector, several of the leading agricultural universities and plant research institutes in the United States (University of California, Cornell, Michigan State, University of Wisconsin, North Carolina State, University of Florida, Ohio State, Rutgers University, Donald Danforth Plant Science Center, and the Boyce Thompson Institute) have joined with the Rockefeller Foundation and McKnight Foundation, both of which support plant biotechnology research in developing countries, to establish a Public-Sector Intellectual Property Resource for Agriculture (PIPRA) (Atkinson, *et al.*, 2003).

These institutions have generated much of the intellectual property in crop biotechnology, but they have also entered into exclusive licensing agreements for this IP with the private sector. These agreements often eliminate their ability to share their technologies with other public-sector institutions, such as national and international research centers that are working on new crop varieties for poor framers in developing countries.

For many of our public universities, the practice of exclusive licensing has also constrained their ability to generate specialty crops for farmers of their own states—a mission that is part of their charters. There are dozens of new transgenic varieties of crops—strawberries, apples, lettuce, *etc.*—in university greenhouses around the country, plants that can grow without pesticides, that would benefit both local farmers and the environment, and that were paid for with taxpayer dollars, but are not being brought to market. Neither the universities nor small companies have sufficient IPR to commercialize them, and the companies that hold the rights are interested only in major crops like corn, soybean, and cotton.

The irony is that, collectively, the universities have exclusively licensed away the IPR they themselves now need. To correct this problem, the institutions involved in PIPRA will promote licensing strategies that favor retention of some of the rights to their own technologies, while still realizing a return on licensing the major market rights to the private sector. The licenses they grant will, therefore, no longer be exclusive. The institutions will retain and share rights to use their technologies for humanitarian purposes, and also for the development of specialty crops for which markets are small and are of no interest to the large private companies. By maintaining a public database, PIPRA will also provide information about technologies that are now available to the public sector without IP constraints. It will also explore IP pooling mechanisms designed to help scientists develop new crops that can truly reach those that are most in need. (More information may be obtained at www.pipra.org.)

The African Agricultural Technology Foundation (AATF) is another new institution the Rockefeller Foundation is helping to establish. It will promote public-private partnerships that benefit African agriculture. The AATF is an African-based, African-led institution, a facilitative organization that will operate by creating partnerships with existing organizations. The AATF will not be aimed primarily at distributing finished products. Rather, it will be a focal point where Africans can access new materials and information on which technologies can be built. It is a way of giving very poor nations the tools to determine what new technologies exist in the public and private sectors, which ones are most relevant to their needs, how to obtain and manage them, and how to develop nationally appropriate regulatory and safety regimes within which to introduce these technologies.

The AATF will transfer materials and knowledge, offering its partners access to advanced agricultural technologies that are privately owned by companies and other research institutions on a royalty-free basis. In exchange for access to these technologies, the AATF will identify partner institutions that can use them to develop new crop varieties that are needed by resource-poor farmers, conduct appropriate biosafety testing, distribute seed to resource-poor farmers, and help create local markets for excess production. Most of the major international seed companies and the United States Department of Agriculture have expressed serious interest in working with the AATF to accomplish its goals. The AATF will provide the organizational stimulus to bring together the elements of the public-private partnerships. The existence of new technologies with great potential, not only for food security but also for income generation by resource-poor producers, and the willingness of companies to collaborate make this the right time to bring these elements together. (More information may be obtained at www.aftechfound.org.)

Regulations

Poor management of IPR is only one of the ways the public sector has been handing over control of agricultural biotechnology to the multinational corporations. As suggested in Figure 2, increasingly onerous and expensive biosafety regulations are also a major cause. In the United States, the cost of obtaining regulatory approval of a new transgenic crop variety can be as much as $30 million. Even the big companies are abandoning research programs if the size of the market does not warrant this level of investment. Small seed and biotechnology companies are essentially priced out of the market unless they partner with the multinationals, and the public sector may be left out as well. Ironically, environmental and consumer groups—who warn against corporate control of agriculture—often work to establish regulations so costly that only multinational corporations can afford to obtain regulatory approvals.

Figure 2. Through exclusive licensing of intellectual property and expensive biosafety regulations, the public sector is enabling a few large multinational chemical companies to gain control over the application of biotechnology to crop improvement.

If developing countries put in place biosafety regulations that are equally onerous, they too are likely to find themselves highly dependent on multinational corporations as their primary sources of advanced new crop varieties. Here again golden rice serves as a good example. If developing countries enact costly biosafety regulations, or if they require golden rice to be approved first in the wealthy countries where it was invented, it will be impossible for the public research institutions that developed it to afford the cost of obtaining regulatory approval.

Regulatory uncertainties and constraints have also delayed commercialization of transgenic crops produced by national researchers in developing countries. In Thailand, scientists working for the National Center for Genetic Engineering and Biotechnology have produced transgenic local varieties of papaya, highly resistant to prevalent strains of papaya ring spot virus. These varieties underwent 3 years of field tests and performed very well, but approvals to commercialize have repeatedly been delayed (McLean, 2003).

As with IPR, the public sector needs to find better and less-expensive ways of addressing legitimate regulatory concerns, if it is to continue to play an important role in producing new crop varieties for the hundreds of millions of small-scale farmers who will not be served by the large companies. If not, the public sector in agriculture may find itself in the same situation as the public sector in health—generating exciting research results, but seeing them used only by the private sector to develop products that can generate profits.

Public Acceptance

Public acceptance of transgenic crops and genetically modified (GM) food, or rather, lack thereof, is a major constraint to the adoption of plant biotechnology, particularly in Europe. This should not be too surprising, since none of the GM products currently on the market provide any benefits to consumers or, for that matter, to food processors or food retailers. Current transgenic crops primarily benefit seed suppliers, farmers, and the rural environment through reduction in insecticide use. Orchestrated campaigns against GM foods have consequently found a receptive audience amongst urban consumers.

The situation in developing countries may well be different. In many, a majority of the population are farmers as well as consumers. They would see the benefits and risks of transgenic crops as farmers and the benefits and risks of GM foods as consumers. As such they would be able to make a much better assessment of overall benefits and risks. They just need to be given the opportunity to do so.

Conclusions

It is easy to reminisce about the good old days when Orville Vogel and Norm Borlaug routinely shared early-generation breeding lines and when breeders from throughout the world could be sent to the United States or Mexico for training and go home with the newest semi-dwarf varieties to test in their own countries. However, a return to those days is neither likely nor truly desirable.

Profit incentives and the private sector do generate and deliver useful products. And, reasonable regulation of new technologies and education of farmers in their application can enhance and prolong their usefulness. Think of the benefits that would be derived if as much effort were put into prolonging the usefulness of natural insect-resistance genes as is now being put into prolonging the usefulness of *Bt* genes. But, in today's global market, property rights, regulations, and liability concerns seem to have gone too far and made access by the poor to new agricultural technologies too difficult.

Getting good farm technology to over two billion poor, small-scale farmers in developing countries in a way that is responsible and sustainable is likely to remain a public-sector responsibility. It will require that governments, public research institutions, non-governmental organizations, and corporations devise new ways of doing business and of forming partnerships that accommodate the interests of the majority of the world's people located in developing countries, as well as the concerns of the technology providers, users who can pay, and consumers in wealthy countries.

REFERENCES

Atkinson RC *et al*. (2003) Public Sector Collaboration for Agricultural IP Management. Science 301 174–175.

Barton J Berger P (2001) Patenting agriculture. Issues in Science and Technology 17 43–50.

Beyer P *et al*. (2002) Golden rice: introducing the β-carotene biosynthesis pathway into rice endosperm by genetic engineering to defeat vitamin A deficiency. Journal of Nutrition 132 506S–510S.

Bustamam M *et al*. (2002) Asian Rice Biotechnology Network: Improving Popular Cultivars Through Marker-Assisted Backcrossing by the NARES. Abstracts of the International Rice Congress, September 16–20, Beijing, China.

Conway G (1999) The Doubly Green Revolution: Food for All in the Twenty-First Century. Ithaca, NY: Cornell University Press.

Delgado C *et al*. (1998) Agricultural Growth Linkages, IFPRI Res. Rep. 107. Washington, DC: International Food Policy Research Institute.

DeVries J Toenniessen G (2001) Securing the Harvest: Biotechnology Breeding and Seed Systems for African Crops. Wallingford: CABI.

Evenson RE Gollin D (2003) Assessing the impact of the green revolution. Science 300 758–762.

Fang X *et al*. (2001) Commercial implementation of intellectual property rights of Chinese transgenic insect-resistance cotton with *Bt* gene and *Bt*+CpT genes. Journal of Agricultural Biotechnology 9 103–106.

FAO (2002a) The State of Food Insecurity in the World. Rome: Food and Agriculture Organization of the United Nations.

FAO (2002b) FAOSTAT. Rome: Food and Agriculture Organization of the United Nations.

FAO (2003) BioDeC Database. Rome: Food and Agriculture Organization of the United Nations.

Hanson H *et al.* (1982) Wheat in the Third World. Boulder, CO: Westview Press.

James C (2002) Global Status of Commercialized Transgenic Crops, ISAAA Briefs, No. 27. Ithaca, NY: International Service for the Acquisition of Agri-biotech Applications.

Jones MP (1999) Basic breeding strategies for high yield rice varieties at WARDA. Japanese Journal of Crop Science 67 133–136.

Kryder DR *et al.* (2000) The intellectual and technical property components of pro-vitamin A rice (Golden Rice), ISAAA Briefs No. 20. Ithaca, NY: International Service for the Acquisition of Agri-biotech Applications.

McLean MA (2003) Case study: the Papaya Biotechnology Network of Southeast Asia, Essential Biosafety, 3rd Edition. Ottawa: Agriculture and Biotechnology Strategies.

Pray C *et al.* (2002) Five years of *Bt* cotton in China—the benefits continue. Plant Journal 31 423–430.

Ribaut JM *et al.* (2002) Use of molecular markers in plant breeding: drought tolerance improvement in tropical maize. In: Quantitative Genetics, Genomics and Plant Breeding (Kang MS ed). WallingfordL CABI International.

Sanchez AC *et al.* (2002) Mapping QTLs associated with drought tolerance in sorghum. Plant Molecular Biology 48 713–726.

United Nations (2002) World Population Prospects: The 2002 Revision. New York: United Nations Population Division.

Wambugu F Kioime R (2001) The Benefits of Biotechnology for Small-Scale Banana Farmers in Kenya, ISAAA Briefs No. 22. Ithaca, NY: International Service for the Acquisition of Agri-biotech Applications.

West KP (2002) Extent of vitamin A deficiency among preschool children and women of reproductive age. Journal of Nutrition 132 2857S–2866S.

World Bank (2003) Millennium Development Goals: Malnutrition and Hunger. Washington, DC: World Bank.

Yadav RS *et al.* (2002) Quantitative trait loci associated with traits determining grain and stover yield in pearl millet under terminal drought-stress conditions. Theoretical and Applied Genetics 104 67–83.