The Future of the Green Revolution: Implications for International Grain Markets

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Abstract

The record of the Green Revolution in Asia shows dramatic increases in wheat production and important but less dramatic increases in rice production, and little effect on maize either in Asia or elsewhere in the developing world. Crop biotechnology, built on molecular manipulations of DNA have been directed toward improving product characteristics, increasing genetic resistance to pests and stress, and increasing crop yields. It appears that annual public and private investment in agricultural biotechnology research may total $2.5 billion, with no more than $75 million in the developing countries. It is likely that the main shifts in comparative advantage will come from changes in the product characteristics of crops rather than from changes in crop yields, the source of the impacts of the first Green Revolution.

The term "Green Revolution" has been used by many different people to mean many different things. Some mean modern agriculture in the developing world, others mean export agriculture in the developing world, still others mean high chemical-input agriculture anywhere. I use the term in a more limited way, to mean the rapid, widespread adoption of semi-dwarf rice and wheat varieties and chemical fertilizer that occurred between 1965 and 1985 in the countries of Asia, and to an extent in Latin America. Asia has been an important player in the international grain market throughout the past 35 years, and the Green Revolution had an important impact on Asia's participation over that period.

Given what is now extremely broad acceptance of semi-dwarf varieties and fertilizer, documented below, any future Green Revolution would have to be generated by a new wave of technological change, presumably generated from biotechnology.

The paper begins with a recapitulation of the Green Revolution record, then considers crop biotechnology and its promise, examines the prospects for significant impact from crop biotechnology, reviews information on donor assistance to biotechnology research in the developing world, and concludes with observations on the impact all this may have on international grain trade.

Green Revolution

According to USDA data, in the 1961-1965 period, world wheat output was 251 million metric tons; by the 1986-1990 period it had doubled to 531 million metric tons. Over the same period South Asia increased its wheat production from 15.5 to 63.5 million metric tons and China increased its wheat production from 19.1 to 90.1 million metric tons. Wheat yields increased about 240% from 825 kg/ha to about 2000kg/ha in South Asia and by 390% from 775 to 3025 kg/ha in China. Thus, while South Asia increased wheat production by 300% and China by 370%, the rest of the world increased production by 70%. This was one of the main reflections of the Green Revolution.

In 1961-65 world rice production averaged 240 million metric tons. It increased to 492 million metric tons in 1986-90. South Asia's rice production went from 72.7 to 135.9 million metric tons, China's went from 72.2 to 176.9 million metric tons over the same period, and South East Asia's went from 49.1 to 106.9 million metric tons. Yield increased by about 160% from 1530 to 2425 kg/ha in South Asia, by about 220% from 2550 to 5450 kg/ha in China, and by about 180% from 1650 to 2950 kg/ha in South East Asia. South Asia's rice production increased 90%, China's increased 140%, SE Asia's increased 120%, while the rest of the world's increased 60%. The Green Revolution in rice was clearly less dramatic than in wheat.

Corn is much less important in Asia than either rice or wheat, and many would say there has been no Green Revolution in corn. At least it has not been generally acknowledged by the community that comments on world food issues. World corn production averaged 214 million metric tons in the 1961-65 period and 456 million metric tons in the 1986-90 period. South Asia's production was only 10 million metric tons in the second period, up from 6 in the first. Corn is moving somewhat more rapidly in China, going from 20 to 80 million metric tons. Data for Africa and Latin America also fail to show much dramatic movement in corn production.

Asia dominates global rice production, while it is just another player in world wheat production, and has been insignificant on the maize scene. Asia's production increases have been much more rapid in wheat than in rice, driven by more rapid increases in yields. Wheat yields averaged 836 kg/ha in South Asia in the early period and increased by 130% to 1978 kg/ha in 1986-90; they averaged 774 kg/ha in China in 1961-65 and increased to 3045 kg/ha later -- an increase of almost 300%. Rice yields, on the other hand increased by 60% in South Asia, by 80% in SE Asia, and by 110% in China.

"Modern" semi-dwarf varieties of both wheat and rice were key to the yield increases that drove the Green Revolution. Adoption rates of modern varieties have been tracked by Dana Dalrymple and the international agricultural research centers associated with their production. China invented semi- dwarfs slightly before and independently of the international centers. The new varieties came out of the centers in the mid-1960s and by 1982 had spread to about 80% of the wheat area in South Asia and to 50% of the rice area in South and South East Asia. By that time farmers in China had started planting hybrid rice, building on their already widespread adoption of semi-dwarfs. By 1990 semi-dwarf wheat had spread to 88% of South Asia's wheat area and semi- dwarf rice to 80% of Asia's rice area.

Irrigated land is also associated with the Green Revolution in Asia. In the 1961-65 period South Asia had 37.6 million hectares of irrigated land; that increased to 63.8

million hectares by the later period, an increase of 70%. China's irrigated area increased from 31.3 million hectares to 45 million, an increase of 40%.

Fertilizer is the third component of the Green Revolution. In 1961-65 South Asia used only 5 kg/ha of fertilizer and China 12; by the 1986-90 period South Asia's farmers were applying an average of 65 kg/ha and China's farmers an average of 240 kg/ha. Fertilizer use increased by factors of 13 in South Asia and 20 in China. In the rest of the world fertilizer use increased by a factor of less than three.

Observers differ on the extent to which the semi-dwarf varieties of wheat and rice were responsible for Asia's Green Revolution. Clearly, fertilizer was an important factor. It is also clear that the semi-dwarf varieties and fertilizer perform much better with irrigation than under rainfed conditions, especially where rainfall is limiting, although both semi-dwarf varieties and fertilizer are applied on rainfed farms in many areas of Asia. As elsewhere, if rainfall distribution or amount limits crop growth, yields are reduced and farmers tend to apply lower rates of fertilizer.

Despite the importance of fertilizer and irrigation, varietal change was a key factor. An analysis of the differences between the capacity of the best rice varieties in India and the United States to respond to fertilizer before the advent of the Green Revolution showed without question the Indian varieties simply could not productively absorb high rates of fertilizer. That ability to productively convert high rates of fertilizer into grain was, in fact, the characteristic of the semi-dwarf varieties that made them so different from earlier varieties. Until that time, low fertilizer use and limited mechanization meant that Asian farm output was generated essentially by inputs produced on farms. Today fertilizer, produced by the industrial sector, is an important source of food.

On the other hand, through the 1990s pesticides have been very little used in Asian wheat production. While the application of fungicides on wheat has become routine in Europe, it is not much used in Asia, and the same can be said for insecticides on wheat. Herbicides are beginning to be used for wheat.

Pesticides and rice are a somewhat different story. The first semi-dwarf rices were vulnerable to the attacks of many insects, and by the early 1970s IRRI research showed that yields with insecticides were higher than without. But in those early studies costs of the pesticides applied were not considered, so rates in excess of economic optima were sometimes used as illustrations of the effect of pesticides. Also, those early pesticide studies failed to account for the natural selection pressure applied to insects that enabled them, in time, to overcome the killing power of the insecticides. By the mid 1980s scientists were developing integrated pest management practices that involved a minimum of insecticide, and today in most Asian countries insecticide application on rice is unnecessary, and often results in lower yields than no application, if used improperly.

Herbicides were of little importance during the Green Revolution when labor was still relatively low cost in Asia and rice was transplanted by hand in rows. More recently, with rising wage rates and migration to the bright lights of the cities, farmers are turning to direct seeding of rice. That makes it necessary to control weeds through use of herbicides, and herbicide use in rice is increasing. This trend has, it seems, convinced Monsanto Corporation that there is a market for their products in rice growing Asia because they are reported to have begun a concerted effort on rice in Asia.

What Is Biotechnology and What is its Promise?

A decade ago some writers used "biotechnology" to refer to such techniques as improved fermentation or cheese making, but while those are biological processes that use technology, most authors now confine their use of the term biotechnology to procedures that use molecular techniques involving DNA. The essence of all DNA is four nucleotides: adenine (A), guanine (G), thymine (T), and cytosine (C). The nucleotides pair up into strands that twist together into the well-know double helix, with A always pairing with T, and G always pairing with C. The entire sequence of base pairs for an organism contains the complete genetic code for that organism, and every cell in the organism contains the entire array of DNA. When cells reproduce, the strands of the double helix separate, and because of the unique pairing, each strand serves as a blueprint for a new strand.

The ability to identify and multiply the DNA sequences which constitute the basic genetic code gives extremely precise ways to identify biological organisms and has led to a number of different kinds of molecular markers and to the capacity to move genetic information from one organism to another without sex -- including across species. Heretofore, inter-specific crosses have been impossible, or in the rare cases where possible, such as crossing a donkey and a horse to get a mule, have resulted in sterile offspring. In essence, biotechnology can be used to modify the genetic composition of organisms in ways that were not possible using conventional breeding.

Genetic transformation and molecular markers are two of the primary tools of biotechnology. Their application to animal agriculture is diverse and complex, in many cases following applications to humans and in other cases breaking new ground. My knowledge does not extend to those many and varied applications, so the rest of the paper is confined to plants.

Transformation enables plant scientists to transfer genes from any source into plants and (sometimes, under some conditions) get stable inter-generational expression of encoded traits. Transformation can be achieved with greater efficiency and more routinely in the dicots than in the monocots, but with determined efforts nearly all plants can be transformed, and monocot transformation is becoming more routine. Marker assisted breeding is used to follow, from one generation to the next, the presence of a particular sequence of DNA and of genes linked to that sequence.

Gene Markers. Far-reaching possibilities for closely identifying genome composition has been made possible through various molecular marker techniques with exotic names like RFLP, RAPD, micro-satellites, and others. These techniques allow scientists to follow genes from one generation to subsequent generations, adding powerfully to the tools at the disposal of plant breeders. In particular, they enable plant breeders to combine several resistance genes, each of which may have different modes of action, leading to longer- acting or more durable resistance against pathogens. Marker tools also facilitate the combining of a number of genes that individually provide only a weakly expressed desirable trait in order to get strong expression.

Transformation and marker assisted breeding have been used toward four broad goals: to change product characteristics, improve plant resistance to pests, increase output, and produce unique metabolites.

Product characteristics. Changed product characteristics are illustrated by one of the first genetically engineered plants to pass regulations and to be made available for general consumption by the public, the FLAVR SAVRTM tomato, whose fruit ripening characteristics have been modified so as to provide a longer shelf life. Biotechnology has also been used to change the proportion of fatty acids in soybeans, modify the composition of oilseed rape (canola) , and change the starch content of potatoes.

Pest resistance. Natural variability in the capacity to resist damage from insects and plant diseases has long been exploited by plant breeders. Biotechnology provides new tools to add to this capacity. Bacillus thuringiensis (Bt) which produces an insect toxin particularly effective against lepidoptera, has been applied to crops by gardeners for decades. Transformation of tomato plants with the gene that produces Bt toxin was one of the first demonstrations of how biotechnology could be used to enhance plants' ability to resist damage from insects. Transgenic cotton that expresses Bt toxin at a level to provide protection against cotton bollworm has been developed , and a large number of Bt transformed crops are currently being field tested. Promoters can be associated with transferred genes to ensure expression in particular plant tissues or at growth stages, and this is one of the strategies being used by scientists to manage the exposure of insects to Bt.

Other approaches to prevent insect damage include transformation of crops with genes of plant origin for proteins that retard insect growth, such as lectins, amylase inhibitors, and protease inhibitors.

Genes providing resistance to viral plant pathogens have been derived from the viruses themselves, most notably with coat protein-mediated resistance (CP- MR); one of the first cases being a yellow squash with CP-MR resistance to two plant viruses approved for commercial production in the United States. Practical resistance to fungal and bacterial pathogens has been more elusive, although genes encoding several enzymes that degrade fungal cell walls have been explored.

Increase yield potential. While protecting plants against insects and pathogens promises to increase harvested output by saving a higher percentage of present yield, a number of scientists are seeking to increase the potential crop yield, including the exploitation of hybrid vigor, delayed senescence, and increased starch.

Several strategies to produce hybrid seed in new ways will likely contribute to increasing yield potential. Cytoplasmic male sterility has been widely used even before biotechnology, but other strategies to exploit nuclear- encoded male sterility required biological manipulations that could only be carried out using molecular biology tools, and now several of these are quite far advanced. Some entail suppression of pollen formation by exploiting sensitivity to temperature or day length. Delayed senescence or "stay-green" trait enables a plant to continue producing photosynthate beyond the period when a non-transformed plant would, thereby potentially producing higher yield. Potatoes that produce higher starch content than non-transformed controls have been developed.

Unique plant metabolites. Plants have been designed to produce a range of lipids, carbohydrates, pharmaceutical polypeptides and industrial enzymes, leading to the hope that plants can be used in place of microbial fermentation. One of the more ambitious of such applications is the production of vaccines against animal or human diseases. The hepatitis B surface antigen has been expressed in tobacco, and the feasibility of using the purified product to elicit an immune response in mice has been demonstrated.

Prospects for Broad Impact

Research continues to improve the efficiency and reduce the costs of the various means of transformation and the several types of genetic markers. As this research succeeds, it will be applied to more plants and genes.

By far the greatest proportion of current crop biotechnology research is being conducted in industrialized countries on the crops of economic interest in those countries. In 1995 almost 2000 plant biotechnology research projects were underway in the 15 countries of the European Union, with 1300 actually using plants (as opposed to plant pathogens, theoretical work and so forth). Of those about 210 were for work on wheat, barley, and other cereals, 150 on potato, 125 on oil seed rape, and about 90 on maize.

Field trials are one of the final stages before seeds are sold to farmers, and reflect the composition of research conducted in earlier years. Between 1986 and the end of 1995, some 3647 field trials had been conducted worldwide, 53% in the United States, 19% in the European Union (almost half in France), 13% in Canada, and the balance in 25 other countries . Argentina, Chile, China and Mexico led in numbers of field trials in developing countries, but none had more than 2% of the total. A rough estimate of R&D biotechnology funding for agriculture suggests $about $2.5 billion is being spent worldwide, with no more than $75 million being spent in developing countries.

Through 1993 the most field trials worldwide were conducted on potato (19%), with oilseed rape second (18%); tobacco, tomato, and maize each accounted for about 12%, with more than 10 trials each on alfalfa, cantaloupe, cotton, flax, sugar beet, soybean, and poplar. Nine trials had been done on rice, and fewer than that on wheat, sorghum, millet, and sugar cane, the food crops that, aside from maize, provide most of the food to most of the worlds's people who live in the developing countries. By the end of 1995, maize, with 33% of field trials worldwide had far surpassed potato (11%), with oilseed rape maintaining second place (21%), and soybean (9%) following potato.

Herbicide resistance is the simplest trait to incorporate into a plant because application of the herbicide applies ideal selection pressure to the population being screened, killing all susceptible individuals. Thus, a population of cells, some containing DNA that confers herbicide resistance, can quickly be screened. A number of different herbicides are available, and there is a strong self-interest on the part of herbicide manufacturers to encourage farmers to use herbicides. This means that several pressures work to ensure that transgenic crops with herbicide resistance will be produced.

Herbicide tolerance has been the most widely tested trait, accounting for 35% of the field trials for agronomically useful genes through 1995. Twenty percent of tests were conducted on 10 different types of modified product quality - including delayed ripening, modified processing characters, starch metabolism, modified oil content.

About 37% of field trials in developing countries were for herbicide resistance, 21% for virus resistance, 26% for insect resistance, 9% for product quality, fungal resistance or agromatic traits. Corn was the subject of the most tests (27%), cotton was the subject of 18% of the trials, with tomato, tobacco, and soybeans each accounting for about 15%, and potato and canola making up most of the rest.

Incorporation of resistance to pests and diseases has been the objective of much of the crop biotechnology work, accounting for 32% of field tests through 1995. This work, as well as the rest of the field trials, is largely focused on temperate area crop pests. It is possible that genes that address insect or disease problems of temperate crops may be effective in tropical crops. But before they can be used in the tropics there still are business and biological problems associated with getting access to the genes, and transforming plants with those genes.

Intellectual property rights may slow the transfer of genes, although in one case, Monsanto has made available, without cost, the genes conferring resistance to important potato viruses to Mexico, and has trained Mexican scientists in transformation and other skills needed to make use of the genes. The transformed potatoes are now being field-tested in Mexico.

Drought is a major problem for nearly all crop plants, and the prospects of a "drought resistance gene" has excited many in the development assistance community. However, plant scientists recognize drought tolerance or resistance as having many dimensions: long, thick roots; thick, waxy leaves; the ability to produce viable pollen under drought stress; the ability to recover from a dry period, and others. Some of these traits can undoubtedly be controlled genetically, but little progress thus far has been made in identifying the genes that control them. Salt tolerance is often discussed with drought tolerance because salt conditions and drought cause plants to react in similar ways, but some of the genes helpful for drought tolerance may be useless for salty conditions and vice versa. Some early workers held out the prospect that by fusing cells of plants tolerant to drought with elite-type plants not tolerant a combination of the two would result, but that has not been demonstrated.

I believe that relatively little attention will be paid to the crops or the pests/diseases/stresses of importance in the developing world unless they are also of importance in the more advanced countries. That is, while the gains in fundamental knowledge that apply to all organisms will, of course, be available to developing countries, the applications in the form of transformation techniques, probes, gene promoters, and genes for specific conditions will not be generated without deliberate efforts aimed at that goal. Hence plant biotechnology progress will be slower in developing than in developed countries.

Pest resistance genes will raise average yields by preventing damage, but there is little prospect for dramatic changes in yield potential through biotechnology. The reason is simple: few strategies are being pursued that attempt to directly raise yield potential because few strategies have been conceived. Hybrid rice is one exception already mentioned. Discussions of other ways of raising yield potential revolve around increasing the "sink" size and increasing the "source" capacity. The first requires increasing the number of grains or the average grain size, the latter increasing the capacity of the plant to fill those grains with carbohydrate. Both are desired but, certainly for rice, there are only a few investigators thinking about how biotechnology might advance each, worldwide. While there is a community of scientists working to understand basic plant biochemistry, including photosynthesis, this work as yet offers few hints about which genes can be manipulated to advantage using molecular biology.

Assistance to Developing Country Plant Biotechnology. It is estimated that between 1985 and 1994 about $260 million was contributed as grants to agricultural biotechnology in the developing world, with another $150 million in the form of loans, with perhaps an average of $50 million per year in the more recent years. At least a third and perhaps half of these funds have been used to establish organizations designed to help bring the benefits of biotechnology to developing countries. This compares to about $200 million annually spent by the federal government alone in the US , with the private sector more than doubling that.

Maize is the focus of much crop biotechnology work in the United States, most of which is directed toward making maize better suited for production or more capable of resisting the depredations of pests in the industrialized countries. The International Wheat and Maize Improvement Center (CIMMYT), sponsors the largest concentration of international effort directed at identifying traits of tropical maize that could be improved using biotechnology, but it spends barely $2 million per year on those efforts. The International Rice Research Institute is probably spending as much on rice biotechnology.

I know of five, coherent, coordinated programs directed specifically at enhancing biotechnology research on developing country crops: one supported by USAID, one by the Dutch government, one by the McKnight Foundation, one by the Rockefeller Foundation, and one by the Asian Development Bank.

The USAID supported project on Agricultural Biotechnology for Sustainable Productivity (ABSP), headquartered at Michigan State University is implemented by a consortium of US Universities and private companies. It is targeted at five crop/pest complexes: potato/potato tuber moth, sweet potato/sweet potato weevil, maize/stem borer, tomato/tomato yellow leaf virus, and cucurbits/several viruses. An outgrowth of the earlier USAID-supported tissue culture for crops project, ABSP builds on the network of scientists associated with the earlier project.

The cassava biotechnology network, sponsored by the Netherlands Directorate General for International Cooperation held its first meeting in August of 1992. It aims to bring the tools of biotechnology to modify cassava so as to better meet the needs of small-scale cassava producers, processors and consumers. Over 125 scientists from 28 countries participated in the first network meeting. Funding to date has been about $2 million. An important initial activity is a study of farmers' needs for technical change in cassava, based on a field survey of cassava producers in several locations in Africa. Funding beyond 1997 is not assured.

The Rockefeller Foundation support for rice biotechnology in the developing world started in 1984. The program has two objectives: to create biotechnology applicable to rice and with it produce improved rice varieties suited to developing country needs, and to ensure that developing country scientists know how to use biotechnology techniques and are capable of adapting them to their own objectives. Approximately $70 million in grants have been made by the program through 1996. A network of about 200 senior scientists and 300 trainee scientists are participating, in all the major rice producing countries of Asia and a number of industrialized countries. Researchers in the network transformed rice in 1988, a first for any cereal. Transformed rice has been field tested in the United States, and a significant number of lines transformed with agronomically useful traits now exist. Molecular maps are being used to assist breeding, and some rice varieties developed by advanced techniques not requiring genetic engineering are now being grown by Chinese farmers.

The McKnight Foundation has provided about $12 million for biotechnology research on agriculturally important problems to a number of teams of researchers from advanced and developing country labs. This innovative program used a global call for proposals and competitive process to award the grants across a range of subject matter of interest to the investigators. The research under the first set of grants is currently underway and no plans have been announced for further funding.

The Asian Development Bank provides about $300,000 annually to fund the Asian Rice Biotechnology Network that links IRRI and Asian countries to share information, and cooperate in the development of tools of biotechnology for rice.

It is unlikely that these five focused crop biotechnology efforts, taken together, entail in excess of $35 mil annually. Total agricultural biotechnology research in the developing world is on the order of $50 million annually. China, India, Egypt, and Brazil and a few other countries have a reasonable base for plant biotechnology.

Implications for Global Grain Markets

What is the likely future of the Green Revolution and what implications does it hold for global grain markets?

First, it is evident that whatever the new tools of biotechnology will contribute towards a future Green Revolution the impact is likely to be gradually spread over a period of years. The impact of the first Green Revolution can barely be discerned in aggregate data, it is unlikely that the impact of molecular biology will be any more dramatic when considered from the global vantage point.

Because the overwhelming majority of plant biotechnology research is being conducted in the industrialized countries, it would seem likely that any changes in comparative advantage that result from the research will work to the advantage of those countries. A massive amount of biotechnology work is being done on corn in the United States. The first wide scale plantings of genetically engineered corn borer-resistant corn and genetically engineered herbicide-resistant soybeans were made in the United States in 1996. There is every indication that the use of these varieties will increase quickly and therefore it would appear that North American production would gain relative to other regions.

However, other innovations may have an offsetting effect. For example, mulch- based, no-till systems have spread to over 6 million hectares in Brazil, with much of that land planted to corn and soybeans. It is difficult to determine the relative cost reducing effects of the no-till and the genetically engineered crops, but that will determine the contribution to any change in comparative advantage across the two regions.

Thus far, relatively little investment has been made in "downstream" biotechnology on wheat in either the industrialized countries or in the developing world, so little impact on global grain markets is to be foreseen from genetic engineering. Rice, on the other hand, has been the subject of concerted biotechnology efforts, in the expectation that improvements in productivity will result. Most of those investments have been by the public sector, with the gene constructs and methods shared across countries. But some countries are better able to apply the knowledge, so one may see some change in relative efficiency from this source. More recently the Monsanto Corporation is reported to have made a decision to enter the Asian rice business, one supposes at least initially with herbicide-resistant rice, so one might expect some gains in efficiency in countries with high labor costs as the herbicide replaces older weed control methods.

Perhaps more important than changes in comparative advantage across regions may be changes in relative efficiency of crops to provide desired product characteristics or functions. Even prior to genetic engineering, conventional breeding methods on oilseed rape produced canola, which has taken market share from corn and other vegetable oils. Oilseed rape has been the subject of extensive and successful genetic engineering efforts, with its composition of fatty acids manipulated in a number of ways. Markets once served by coconut and soybeans have been eroded by this rapeseed, and further changes are likely.

One can conceive of productivity or product changes that might cause the substitution of one grain for another, or perhaps even the substitution of cassava for grains, but as far as I am aware, any such efforts are at an early stage, and would not lead to such results in the foreseeable future. To the contrary, most research seems aimed at either offsetting specific pest problems or incorporating specific quality traits.

The discussion of the preceding section shows that the efforts directed at biotechnology for developing country agriculture are small, especially when compared to those directed at the industrialized world. Still, some important contributions should come from the former. Training of developing country scientists under various programs mean there is a small cadre of plant molecular biologists in a number of developing countries.

The Rockefeller Foundation's support to rice biotechnology is beginning to pay off in the form of new rice varieties available to some Asian farmers. In China, a rice variety produced at the Shanghai Academy of Agricultural Sciences through anther culture, which incorporates genes for resistance to pathogens and cold, has been field tested on over 3000 hectares in Anhui and Hubei provinces, resulting in yields from 6 to 24 percent higher than the most popular previous varieties.

We expect that the contributions to rice yield increases from biotechnology in Asia will be on the order of 10-25% over the next ten years. These will come from improved hybrid rice systems largely in China, and in other Asian countries from rice varieties transformed with genes for resistance to pests and diseases.

The speed with which varieties get into farmers' hands depends largely on national conditions -- the closeness of linkages between biotechnologists and plant breeders, the ability of scientists to identify the most limiting conditions, identify genes that overcome those constraints and get those genes into good agronomic backgrounds, and the efforts plant scientists and others have put into crafting biosafety regulations.

Developing country maize yields may be affected by biotechnology if genes useful in tropical countries are discovered in the course of the massive work being done on maize in the United States. Although most of the maize work is being done by private firms, it is not unlikely that some of the discoveries will be made available for application in developing countries either at no cost or at low enough cost as to make their use commercially feasible. Biotechnology applications on cassava are further in the future, as are those on smallholder banana and other crops of importance in the developing world.

My own conclusion is that factors other than biology are likely to be more important to future global grain markets, at least more important than the productivity effects of biotechnology. For one, the public apprehension about biotechnology coupled with opportunism have already led to demands for trade barriers against genetically engineered crops.

While modern wheat also spread in North Africa and the Republic of South Africa over that period, the area of wheat in Africa is very relative to global food or international trade.

Data in this section from the USDA on-line database World Agricultural Trends and Indicators, 1996.

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