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# Bioengineering of Crops

*Report of the World Bank Panel  
on Transgenic Crops*

*Henry W. Kendall, Roger Beachy, Thomas Eisner,  
Fred Gould, Robert Herdt, Peter H. Raven,  
Jozef S. Schell, and M.S. Swaminathan*

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Washington, D.C.*

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# Introduction

The primary objectives of the World Bank Group are to alleviate poverty, malnutrition, and human misery in developing nations while encouraging and supporting a transition to environmentally sustainable activities. The issue of providing adequate food, based on sustainable agricultural practices, looms large in gaining these objectives, for failure in this area will virtually guarantee failure to meet other objectives. Moreover, failure will make certain continued misery for many of our fellow human beings. Agricultural systems are already under stress, and they will become more stressed as populations continue to swell and the need for food supplies increases.

The World Bank has made important contributions to the alleviation of hunger and malnutrition through its programs that aid agriculture in the developing world. Its aid was a major factor in making India self-sufficient in food production in the difficult time after World War II. Similarly, its support to the Consultative Group on International Agricultural Research (CGIAR) was instrumental in enabling the CGIAR to be a major player in introducing the Green Revolution, which contributed so much to economic growth in the developing world.<sup>1</sup> But despite contributions by the Bank and other organizations and by nations, the need to enhance food security in much of the developing world will remain a critical problem for many years to come.

Among the numerous approaches to expanding food supplies in the developing world in environmentally benign ways is the bioengineering of crops. Bioengineering has

much to contribute, but it is a novel system and possible risks need to be evaluated carefully. Opposition to bioengineering research and its application has already arisen, not all of it carefully thought out. As the World Bank has recognized, a considered and technically competent understanding of both the potential and the perceived risks of bioengineered crops is a requisite to their successful development and use. Public perceptions that genetically engineered crops and animal products pose specific dangers must be carefully considered and addressed if such products are to reach widespread use.

In 1996 Ismail Serageldin, the World Bank's vice president for Environmentally and Socially Sustainable Development and chairman of the CGIAR, initiated a study panel to assess the potential of crop bioengineering as well as the inherent risks. The panel was to provide the Bank with guidance in its activities, including its support to the CGIAR. This is the panel's report.

In what follows we review the status of world food supplies and the prospects and needs for the future with emphasis on the developing world. We then describe bioengineering technology and the potential contributions that transgenic crops might make to the alleviation of problems of food security. After that we deal with possible risks from the widespread deployment of genetically altered crops. Finally, we offer some conclusions and recommendations.

## Note

1. Henry Owen, "The World Bank: Is 50 Years Enough?" *Foreign Affairs* 73 (September/October 1994): 99.



# World Food Supplies

**C**urrent and future demands for food and the pressures and stress on the world's agricultural sector generate the need to set priorities among a cluster of problems and available solutions, including the bioengineering of crops.<sup>1</sup> This section of the report sets out and assesses the challenges as they stand today and evaluates what the future may bring.

### Current Circumstances

We are now facing the following challenges.

#### *Population*

The world's population stands at 5.8 billion and is growing at about 1.5 percent a year. The industrial, wealthy nations, including Japan and the nations of Europe and North America, have about 1.2 billion people. These nations are growing at a slow rate, roughly 0.1 percent a year.

Population in the developing world is 4.6 billion and is expanding at 1.9 percent a year, a rate that has been decreasing somewhat in the past decade. The least developed nations, with a total population of 560 million, are growing at 2.8 percent a year. If they continue to grow at this rate, their population will double in twenty-four years. At present about 87 million people are added to the world's population each year.

#### *Food: Nutrition and Malnutrition*

The wealthy nations have high levels of nutrition and little problem supplying all their citi-

zens with adequate food when they wish to do so. Indeed, well over one-third of world grain production is fed to livestock to enhance the supply of animal protein, which is consumed most heavily in the industrial world.

In the developing world, matters are different. More than 1 billion people do not get enough to eat on a daily basis and live in what the World Bank terms "utter poverty"; about half of that number suffer from serious malnutrition. A minority of nations in the developing world are markedly improving their citizens' standard of living: in some fifteen countries 1.5 billion people have experienced rapidly rising incomes over the past twenty years. But in more than a hundred countries 1.6 billion people have experienced stagnant or falling incomes. Since 1990 incomes have fallen by a fifth in twenty-one countries of eastern Europe.

Had the world's food supply been distributed evenly in 1994, it would have provided an adequate diet of about 2,350 calories a day per person for 6.4 billion people, more than the actual population.<sup>2</sup>

In addition to the food shortages suffered by many in developing countries, there are widespread deficiencies in certain vitamins and minerals. Vitamin A appears to be lacking from many diets, especially in Southeast Asia, and there is deficiency in iron, which contributes to widespread anemia among women in the developing world.<sup>3</sup>

Food prices have been declining over the past several decades, and some observers have argued that the decline is a sign that adequate food for all is now available. But those in utter

poverty do not have the resources to purchase adequate food, even at today's prices. More recently, food prices have risen, while grain stocks have fallen to their lowest level in thirty years.<sup>4</sup>

### *Agriculture*

About 12 percent of the world's total land surface is used to grow crops, about 30 percent is forest or woodland, and 26 percent is pasture or meadow. The remainder, about one-third, is used for other human purposes or is unusable because of climate or topography. In 1961 the amount of cultivated land supporting food production was 0.44 hectares per capita. Today it is about 0.26 hectares per capita, and based on population projections, it will be in the vicinity of 0.15 hectares per capita by 2050.<sup>5</sup> The rate of expansion of arable land is now below 0.2 percent a year and continues to fall. The bulk of the land best suited to rainfed agriculture is already under cultivation, and the land that is being brought into cultivation generally has lower productivity.

Urbanization frequently involves the loss of prime agricultural land, because cities are usually founded near such land. Losses of prime land are often not counterbalanced by the opening of other lands to production because the infrastructure that is generally required for market access is frequently lacking on those lands.

Irrigation plays an important role in global food production. Of the currently exploited arable land, about 16 percent is irrigated, producing more than one-third of the world crop. Irrigated land is, on balance, over two and a half times more productive than rainfed land.

The situation in India and China is particularly acute because their people account for nearly half of the developing world's population. Both countries have expanding populations and diminishing per capita arable land and water resources. The average farm size in both countries is one hectare or less. Agriculture, including crop and animal husbandry, forestry, and fisheries, has been a way of life and a means to achieve a livelihood for several thousand years. Expansion in population and increases in purchasing power, coupled with the diversion

of prime farm land for nonfarm uses, make it essential for these two countries to adopt ecologically sustainable, intensive, and integrated farming systems (see appendix).

In China land is communally owned but individually cultivated under the country's Household Responsibility System. In India land is individually owned and agriculture constitutes the largest private-sector enterprise in the country. India's population of 950 million is growing at about 1.9 percent annually, while China's stands at 1.22 billion and is growing at 1.1 percent a year. China has nearly 50 percent of its cultivated land under irrigation, while less than 30 percent of India's cultivated area is irrigated.<sup>6</sup>

Agriculture in both countries must provide not only more food but also more employment and income. Modern industry is frequently associated with economic growth, but growth without adequate expansion of employment. Modern agriculture can foster job-led economic growth. Therefore, farming cannot be viewed in either country as merely a means of producing more food and other agricultural commodities; instead, it must be looked upon as the very foundation of a secure livelihood. New technologies, such as biotechnology, information and space technologies, and renewable energy, are pivotal to building vibrant agricultural sectors, to producing more from less land and water, and to strengthening local economies.

### *Pressures on Agricultural Systems*

Widespread injurious agricultural practices, in both the industrial and the developing worlds, have damaged the productivity of land, in some cases severely.<sup>7</sup> These practices have led to water- and wind-induced erosion, salination, compaction, waterlogging, overgrazing, and other problems. For example, the estimated loss of topsoil in excess of new soil production is estimated to be about 0.7 percent of the total topsoil each year; this loss amounts to some 25 billion tons, equivalent to the total in Australia's wheat growing area. An additional 0.7 percent annual loss occurs from land degradation and the spread of urbanization. Erosion has made a billion hectares of soil unusable for agriculture over past years.<sup>8</sup> Asia has the highest percentage

of eroded land, nearly 30 percent, but in all major regions the percentage exceeds 12.<sup>9</sup> It is estimated that 17 percent of all vegetated land was degraded by human activity between 1945 and 1990.

The effects of erosion on crop yield are not well documented because researching such effects is difficult and expensive and because degradation can be masked for short periods of time by more intensive agricultural practices. However certain data are available.<sup>10</sup> Erosion can ultimately destroy the land's productive capacity by stripping off all of the soil, as has occurred in Haiti. "Haiti suffers some of the world's most severe erosion, down to bedrock over large parts of some regions, so that even farmers with reasonable amounts of land cannot make a living."<sup>11</sup>

Irrigation practices continue to contribute to salinization and other forms of land damage. For example, more than half of all irrigated land is in dry areas, and 30 percent of that land is moderately to severely degraded. Salinization is a serious problem in Australia, Egypt, India, Mexico, Pakistan, and the United States. Some 10 percent of the world's irrigated land suffers from salinization.

There are also serious problems with supplies of water—much of the world is in short supply.<sup>12</sup> Worldwide, nations with some 214 river or lake basins and 40 percent of the world's population now compete for water.<sup>13</sup> Much irrigation depends on "fossil" underground water supplies, which are being pumped more rapidly than they are being recharged.<sup>14</sup> This problem affects portions of Africa, China, India, the United States, and several countries in the Middle East, especially Israel and Jordan. The human race now uses 26 percent of the total terrestrial evapotranspiration and 54 percent of the fresh water runoff that is geographically and temporally accessible. Most land suitable for rainfed agriculture is already in production.<sup>15</sup>

It is now clear that agricultural production is currently unsustainable. Indeed, human activities, as they are now conducted, appear to be approaching the limits of the earth's capacity. These unsustainable activities, like all unsustainable practices, must end at some point. The end will come either from changes that establish

a basis for a humane future or from partial or complete destruction of the resource base, which would bring widespread misery.

## The Future

In future years we are likely to face the following challenges.

### *Population*

Although fertility has been declining worldwide in recent decades, it is not known when it will decline to replacement level. There is broad agreement among demographers that if current trends are maintained, the world's population will reach about 8 billion by 2020, 10 billion by 2050, and possibly 12 to 14 billion before the end of the next century. Virtually all of the growth in coming decades will occur in the developing world.

### *Food Demand*

To provide increased nutrition for a growing world population, it will be necessary to expand food production faster than the rate of population growth. Studies forecast a doubling in demand for food by 2025–30.<sup>16</sup> Dietary changes and the growth in nutritional intake that accompany increased affluence will contribute to making food demand larger than the projected increase in population.

Asia, which has 60 percent of the world's population, contains the largest number of the world's poor; 800 million people in Asia live in absolute poverty and 500 million live in extreme poverty. Projections by the United Nations Food and Agriculture Organization (FAO), the World Bank, and the International Food Policy Research Institute show that the demand for food in Asia will exceed the supply by 2010.<sup>17</sup> China, the world's most populous nation, has more than 1.2 billion people and an annual growth rate of 1.1 percent a year. The country will face considerable challenges in years ahead from stress resulting from major environmental damage, shortages of water, and diversion or degradation of arable lands.<sup>18</sup> Animal protein has increased in the Chinese diet from about 7

percent in 1980 to more than 20 percent today, aggravating the country's food challenges. Most of the water available in China is used for agriculture, and heavy use of fertilizers has polluted much of the water supply.

Lester Brown and Hal Kane have argued that by 2030 India will need to import 45 million tons of food grain annually and China 216 million tons to feed their growing populations.<sup>19</sup> The widening gap between grain production and consumption in the two countries, caused by increases in population and purchasing power, will lead to the need for such imports. Brown and Kane have pointed out that while demand will grow, production prospects are not bright owing to stagnation in applying yield-enhancing technologies and growing damage to the ecological foundations essential for sustainable advances in farm productivity. It is apparent that without substantial change there will not be enough grain to meet the needs of the two countries, a conclusion that at least some Chinese scholars agree with.<sup>20</sup>

Latin America, which is economically and demographically advanced compared with Africa and Asia, appears to enjoy a relatively favorable situation with respect to food supplies and food security. Some regions are, however, under stress because of economic problems and continuing high rates of population increase. Bolivia, northeast Brazil, Peru, much of Central America, and parts of the Caribbean, especially El Salvador, Guatemala, Haiti, and Honduras, face important challenges. Latin America's population is expected to increase from 490 million to nearly 680 million by 2025, and it is possible that more than a quarter of the area's annual cereal consumption will be imported by 2020. The major countries in the region, including Argentina, Brazil, Chile, Colombia, and Mexico, appear to have the resources necessary to meet their projected food needs, but doing so will require maintaining stable populations and implementing successful land management programs.<sup>21</sup>

Countries in the Middle East and North Africa have seen demand for food outpace domestic production. Differences in oil wealth and agricultural production determine differences in ability to import grains and livestock

products.<sup>22</sup> The greatest challenges will be faced by nations that lack the capacity for substantial oil exports or other sources of wealth with which to purchase food imports. These nations include Afghanistan, Cyprus, Egypt, Jordan, Lebanon, Mauritania, Somalia, Tunisia, and Yemen, whose combined population exceeded 125 million in 1994. Food self-sufficiency is unattainable for most of these countries. Oil exporting nations will, as their oil resources dwindle, join this less fortunate group.

Sub-Saharan Africa is the region whose prospective food supplies generate the greatest concern; since 1980 agriculture there has grown at 1.7 percent a year, while population, now at 739 million, has grown at 2.9 percent a year.<sup>23</sup> Some twenty years ago, Africa produced food equal to what it consumed; today it produces only 80 percent of the food it consumes.<sup>24</sup> With a population growth rate of close to 3 percent a year, Sub-Saharan Africa cannot close its food gap. The gap will likely grow, requiring increased imports of food to prevent growing malnutrition and increased risk of famine. If present worldwide decreases in foreign aid persist, these imports may not be forthcoming.

### *Agriculture and Irrigation*

As described above, the current rates of injury to arable land are troubling. Since 1950, 25 percent of the world's topsoil has been lost, and continued erosion at the present rate will result in the further irreversible loss of at least 30 percent of the global topsoil by the middle of the next century. A similar percentage may be lost to land degradation, a loss that can be made up only with the greatest difficulty through conversion of pasture and forest, themselves under pressure. In Asia 82 percent of the potentially arable land is already under cultivation. Much of the land classed as potentially arable is not available because it is of low quality or easily damaged.

The FAO has projected that over the next twenty years arable land in the developing countries could be expanded by 12 percent at satisfactory economic and environmental costs, although such expansion would inflict major damage to the world's remaining biodiversity.<sup>25</sup> The yields per hectare on this land would be less than on the

land already in production. This expansion is to be compared with the 61 percent increase in food demand that is expected to occur in these countries during the same period, according to a scenario discussed by the FAO. The last major frontiers that can potentially be converted to arable land are the acid soil areas of the Brazilian cerrado, the llanos of Colombia and Venezuela, and the acid soil areas of central and southern Africa. Bringing these unexploited, potentially arable lands into agricultural production poses formidable but not insurmountable challenges.<sup>26</sup>

The prospects for expanding irrigation, so critical to the intensification of agricultural productivity, are also troubling. The growth of irrigated land has been slowing since the 1970s, owing to the problems discussed above as well as to "siltation" of reservoirs and the environmental problems and related costs that arise from the construction of large dam systems. The problems can include the spread of disease.

An important "wild card" in any assessment of future agricultural productivity is climatic change resulting from anthropogenic emissions of greenhouse gases. The consequences of such change touch on a wide range of technical issues that will not be summarized here.<sup>27</sup> However, the Intergovernmental Panel on Climate Change (IPCC) concluded in its second assessment report that the balance of evidence suggests that there is a discernable human influence on climate and that a global warming of about two degrees Celsius, with a range of uncertainty from one to three and a half degrees Celsius, will occur by 2100. The consequences of a two-degree warming would include regional and global changes in climate and climate-related parameters such as temperature, precipitation, soil moisture, and sea level. These changes could in turn give rise to regional increases in "the incidence of extreme high temperature events, floods, and droughts, with resultant consequences for fires, pest outbreaks and ecosystem composition, structure and functioning, including primary productivity."<sup>28</sup> According to the IPCC:

Crop yields and changes in productivity due to climate change will vary considerably across regions and among localities, thus changing the patterns of

production. Productivity is projected to increase in some areas and decrease in others, especially the tropics and subtropics. . . . There may be increased risk of hunger and famine in some locations; many of the world's poorest people—particularly those living in subtropical and tropical areas and dependent on isolated agricultural systems in semi-arid and arid regions—are most at risk of increased hunger. Many of these at-risk populations are found in Sub-Saharan Africa; South, East, and Southeast Asia; and tropical areas of Latin America, as well as some Pacific island nations.<sup>29</sup>

Further deleterious changes may occur in livestock production, fisheries, and global supplies of forest products. Salt intrusion into coastal area aquifers, many of which supply water for irrigation, can occur as a result of rising sea levels. While important uncertainties about climatic change and its consequences will remain for some years, the matter must be considered in assessing the prospects for expanding nutrition in the developing world.

### *Prospects*

Today, there are hundreds of millions of people who do not get enough food. Given the circumstances described above, it appears that over the next quarter century grave problems of food security will almost certainly affect even more people, as a number of observers have pointed out.<sup>30</sup>

Given present knowledge, therefore, maximum realization of potential land, and water, supplies at acceptable economic and environmental costs in the developing countries still would leave them well short of the production increases needed to meet the demand scenarios over the next twenty years.<sup>31</sup>

The task of meeting world food needs to 2010 by the use of existing technology may prove difficult, not only because of the historically unprecedented incre-

ments to world population that seem inevitable during this period but also because problems of resource degradation and mismanagement are emerging. Such problems call into question the sustainability of the key technological paradigms on which much of the expansion of food production since 1960 has depended.<sup>32</sup>

As is the case now, those in the lower tier of the developing countries will continue to be most affected by shortfalls in food production. The industrial nations and the developing nations whose economies continue to improve will face acceptable costs in providing their citizens with adequate nutrition. The extent of deprivation and economic and environmental costs remains the subject of controversy between optimists and pessimists.<sup>33</sup>

### Meeting the Challenges

The main challenge is to expand agricultural production at a rate exceeding population growth in the decades ahead so as to provide food to the hungry new mouths to be fed. This goal must be accomplished in the face of a fixed or slowly growing base of arable land offering little expansion, and it must involve simultaneous replacement of destructive agricultural practices with more benign ones. Thus the call for agricultural sustainability.<sup>34</sup> Owing to the daunting nature of this challenge, every economically, ecologically, and socially feasible improvement will have to be carefully exploited. A list of potential improvements includes:

- Introducing energy-intensive farming, including, in some areas, increased fertilizer use
- Conserving soil and water, with special priority given to combating erosion
- Maintaining biodiversity
- Improving pest control
- Expanding irrigation and making it more efficient
- Improving livestock management
- Developing new crop strains with increased yield, pest resistance, and drought tolerance
- Reducing dependency on pesticides and herbicides.

The application of modern techniques of crop bioengineering could be a key factor in implementing many of these improvements. These techniques are a powerful new tool with which to supplement pathology, agronomy, plant breeding, plant physiology, and other approaches that serve us now.

If crop bioengineering techniques are developed and applied in a manner consistent with ecologically sound agriculture, they could decrease reliance on broad spectrum insecticides, which cause serious health and environmental problems. This reduction could be accomplished by breeding crop varieties that have specific toxicity to target pests but do not affect beneficial insects. Furthermore, bioengineering techniques could assist in the development of crop varieties that are resistant to currently uncontrollable plant diseases. At their best bioengineering techniques are highly compatible with the goals of sustainable agriculture because they offer surgical precision in combating specific problems without disrupting other functional components of the agricultural system.

While it is feasible to use biotechnology to improve the ecological soundness of agriculture, well-informed decisions must be made regarding which specific biotechnology projects are encouraged and which are discouraged. For example, ten years ago, when crop bioengineering was being introduced in the United States, some projects were focused on engineering crops for tolerance against a dangerous herbicide. The projects were dropped after environmental groups protested. Projects targeted for developing countries will have to be scrutinized to make sure that their long-term impacts are beneficial.

Not all challenges to sustainable and productive agriculture can be addressed with biotechnology. For example, improving soil and water conservation, maintaining biodiversity, and improving irrigation techniques must be dealt with by other means.

We must emphasize that the improvements in agriculture described in this report, while badly needed, do not address all of the difficulties faced by the lower tier of developing nations. There is almost no dispute that careful planning and selection of priorities, coupled with substantial commitments from both indus-

trial and developing nations, will be required to provide the food supplies that the future will demand, to move to sustainable agricultural practices, and to alleviate hardship in now-impooverished nations.

## Notes

1. See H. W. Kendall and David Pimentel, "Constraints on the Expansion of the Global Food Supply," *AMBIO* 23 (May 1994): 198–205.
2. Norman E. Borlaug, "Feeding the World: The Challenges Ahead," in *Meeting the Challenges of Population, Environment, and Resources: The Costs of Inaction*, H. W. Kendall and others. (Washington, D.C.: World Bank, 1996).
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# Bioengineering Technology

Plant scientists can now transfer genes into many crop plants and achieve stable inter-generational expression of new traits. "Promoters" (deoxyribonucleic acid [DNA] sequences that control the expression of genes, for example) can be associated with transferred genes to ensure expression in particular plant tissues or at particular growth stages. Transformation can be achieved with greater efficiency and more routinely in some dicots (for example, tomatoes, potatoes) than in some monocots (for example, rice and wheat), but with determined effort nearly all plants can or will be modified by genetic engineering.

### Gene Transformation

Genetic transformation and other modern crop breeding techniques have been used to achieve four broad goals: to change product characteristics, improve plant resistance to pests and pathogens, increase output, and improve the nutritional value of foods.

Genetic modification to alter product characteristics is illustrated by the Flavr Savr™ tomato, one of the first genetically engineered plants to receive approval from the U.S. Food and Drug Administration and to be made available for general consumption by the public; the fruit ripening characteristics of this variety were modified to provide a longer shelf life.<sup>1</sup> Biotechnology has also been used to change the proportion of fatty acids in soybeans, modify the composition of canola oil, and change the starch content of potatoes.<sup>2</sup>

Natural variability in the capacity of plants to resist damage from insects and diseases has

long been exploited by plant breeders. Biotechnology provides new tools to the breeder to expand plant capacity. In the past crop breeders were generally limited to transferring genes from one crop variety to another. In some cases they were able to transfer useful genes to a variety from a closely related crop species or a related native plant. Genetic engineering now gives plant breeders the power to transfer genes to crop varieties independent of the gene's origin. Thus bacterial and even animal genes can be used to improve a crop variety.

*Bacillus thuringiensis* (Bt), a bacterium that produces an insect toxin particularly effective against lepidoptera (such as caterpillars and moths), has been applied to crops by gardeners for decades. It is also effective against mosquitoes and certain beetles. Transformation of tomato and tobacco plants with the gene that produces Bt toxin was one of the first demonstrations of how biotechnology can be used to enhance a plant's ability to resist damage from insects.<sup>3</sup> Transgenic cotton that expresses Bt toxin at a level providing protection against cotton bollworm has been developed, and a large number of Bt-transformed crops, including corn and rice, are currently being field tested.<sup>4</sup> Other strategies to prevent insect damage include using protein coding genes of plant origin, such as lectins, amylase inhibitors, protease inhibitors, and cholesterol oxidase, that retard insect growth.<sup>5</sup>

Genes that confer resistance to viral diseases have been derived from the viruses themselves, most notably with coat protein mediated resistance (CP-MR). Following extensive field evalu-

ation, a yellow squash with CP-MR resistance to two plant viruses was approved for commercial production in the United States.<sup>6</sup> Practical resistance to fungal and bacterial pathogens has been more elusive, although genes encoding enzymes that degrade fungal cell walls or inhibit fungal growth are being evaluated. More recently, natural genes for resistance to pathogens have been cloned, modified, and shown to function when transferred to susceptible plants.<sup>7</sup>

While protecting plants against insects and pathogens promises to increase crop yield by saving a higher percentage of present yield, several strategies seek to increase the potential crop yield. These strategies include exploiting hybrid vigor, delaying plant senescence, and inducing plants to flower earlier and to increase starch production.

Several strategies to produce hybrid seeds in new ways will likely contribute to increasing yield potential. Cytoplasmic male sterility was widely used long before the age of biotechnology, but strategies to exploit male sterility require biological manipulations that can only be carried out using tools from molecular biology; several of these strategies are well advanced.<sup>8</sup> Some of the strategies entail suppressing pollen formation by changing the temperature or day length. Delayed senescence or "stay-green" traits enable a plant to continue producing food beyond the period when a non-transformed plant would, thereby potentially producing a higher yield.<sup>9</sup> Potatoes that produce higher starch content than nontransformed control potatoes have been developed.<sup>10</sup>

Plants have been modified 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.<sup>11</sup> One of the more ambitious of such applications is the production of vaccines against animal and 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.<sup>12</sup>

### Gene Markers

Far-reaching possibilities for identifying genes have been made possible through various mole-

cular marker techniques with exotic names such as restriction fragment length polymorphism (RFLP), random amplified polymorphic DNA (RAPD), and microsatellites. These techniques allow scientists to follow genes from one generation to the next, adding to the tools at the disposal of plant breeders. In particular, the techniques 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. Marking also makes it possible for the breeder to combine several genes, each of which may individually provide only a weakly expressed desirable trait but in combination have higher activity.

### Ongoing Research

Research continues to improve the efficiency and reduce the costs of developing transgenic crops and using genetic markers. As this research succeeds, it will be applied to different plants and genes.

By far the greatest proportion of current research in crop biotechnology is being conducted in industrial countries on the crops of economic interest in those countries. Plant biotechnology research in the fifteen countries of the European Union is probably a fair reflection of current global research in plant biotechnology. Almost 2,000 projects are under way, 1,300 of them actually using plants (as opposed to plant pathogens, theoretical work, and the like). About 210 of the projects using plants are on wheat, barley, and other cereals; 150 of the projects are on the potato; 125 are on oilseed rape; and about 90 are on maize.<sup>13</sup>

The worldwide record of field trials reflects the focus of research activities, and the record shows that work on cereals was started somewhat later than work on other plants. Some 1,024 field trials were conducted worldwide through 1993; 88 percent of those trials were in Organization for Economic Cooperation and Development (OECD) countries, with 38 percent in the United States, 13 percent in France, and 12 percent in Canada. Belgium, the Netherlands, and the United Kingdom each hosted about 5 percent of the total number of

field trials. Argentina, Chile, China, and Mexico led in numbers of trials in developing countries, but none had more than 2 percent of the total.<sup>14</sup>

The largest number of field trials was conducted on the potato (19 percent). Oilseed rape accounted for 18 percent of the field trials, while tobacco, tomatoes, and maize each accounted for about 12 percent. There were more than ten trials each on alfalfa, cantaloupe, cotton, flax, sugar beet, soybean, and poplar. Nine tests were done on rice, and fewer than nine on wheat, sorghum, millet, cassava, and sugarcane, the crops that, aside from maize, provide most of the food to most of the world's people, who live in the developing countries.

Herbicide tolerance has been the most widely tested genetically engineered trait, accounting for 40 percent of the field trials for agronomically useful transgenes. Twenty-two percent of tests were conducted on ten different types of modified product quality, including delayed ripening, modified processing characters, starch metabolism, and modified oil content.<sup>15</sup> About 40 percent of field trials in developing countries were for virus resistance. Twenty-five percent of the trials were for crops modified for herbicide resistance, and another 25 percent were for insect resistance, with the balance for product quality, fungal resistance, or aromatic traits.<sup>16</sup>

Although much of the biotechnology research in agriculture has focused on bioengineering (that is, gene transfer), the techniques of biotechnology extend beyond this approach. The techniques involved in tissue culture have been advanced and refined over the past decade. These techniques can be used to regenerate plants from single cells and have proven especially useful in producing disease-free plants that can be propagated and distributed to farmers. The use of these plants has resulted in significant yield improvements in crops as diverse as potato and sugarcane.

Another use for biotechnology is in developing diagnostic techniques. Too often, poorly performing crops have observable symptoms that are so general that the farmer cannot determine the specific cause. For example, Tungro disease in rice produces symptoms that match those of certain nutrient deficiencies. Biotechnology

techniques can be used to develop easy-to-use kits that can alert the farmer to the presence of deoxyribonucleic acid (DNA) from the Tungro virus in rice plants. Such knowledge can decrease the frustration and money spent on solving the wrong problem.

### Current Efforts

Most biotechnology research in industrial countries is being conducted on human health issues rather than on agriculture. Government spending for biotechnology research in the United States is about \$3.3 billion a year, with \$2.9 billion going to health issues and \$190 million to agricultural issues.<sup>17</sup> It is estimated that between 1985 and 1994 \$260 million was contributed in the form of grants to agricultural biotechnology in the developing world; another \$150 million was contributed in the form of loans. An average of perhaps \$50 million a year has been contributed in more recent years.<sup>18</sup> 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.

Maize is the focus of much crop biotechnology work in the United States. Most of this work on maize is directed toward making it better suited for production or more capable of resisting the depredations of the pests in industrial countries. The International Wheat and Maize Improvement Center sponsors the largest international effort directed at identifying traits of maize that could be improved using biotechnology, but the center spends barely \$2 million a year on those efforts.

There are, at present, only four coherent, coordinated programs directed specifically at enhancing biotechnology research on crops in developing countries, one supported by the U.S. Agency for International Development (USAID), one by the Dutch government, one by the Rockefeller Foundation, and one by the McKnight Foundation.

The USAID-supported project, Agricultural Biotechnology for Sustainable Productivity (ABSP), is headquartered at Michigan State University and implemented by a consortium of U.S. universities and private companies. It is tar-

geted at five crop/pest complexes: the potato and the potato tuber moth, the sweet potato and the sweet potato weevil, maize and the stem borer, the tomato and the tomato yellow leaf virus, and cucurbits and several viruses. The ABSP is an outgrowth of an earlier USAID-supported project on improving tissue culture techniques for crops. It builds on the network of scientists associated with that earlier project and draws on other scientists as well.

The cassava biotechnology network, sponsored by the Netherlands Directorate General for International Cooperation, held its first meeting in August 1992. Its goals include using the tools of biotechnology to modify cassava to better meet the needs of small-scale cassava producers, processors, and consumers. More than 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. The study will be based on a field survey of cassava producers in several locations in Africa.

Another important initiative, the International Laboratory of Tropical Agricultural Biotechnology, is being developed at the Scripps Institute in La Jolla, California. It is jointly administered by the institute and by L'Institut français de recherche scientifique pour le développement en coopération (ORSTOM), a French governmental development agency. Funding for research in the control of diseases of rice, cassava, and tomato through applications of biotechnology is provided in grants from ORSTOM, the Rockefeller Foundation, the ABSP, and USAID. Most of the research is carried out by fellows, students, and other trainees from developing countries.

The Rockefeller Foundation began to support rice biotechnology in the developing world in 1984. The foundation's program has two objectives: (1) to create biotechnology applicable to rice to produce improved rice varieties suited to developing country needs and (2) to ensure that scientists in developing countries know how to use biotechnology techniques and are capable of adapting the techniques to their own objectives. Approximately \$50 million in grants have been made through the program.

About two hundred senior scientists and three hundred trainee scientists are participating in the program. The scientists are spread throughout all the major rice-producing countries of Asia and a number of industrial countries. Researchers from the group transformed rice in 1988, a first for any cereal. Transformed rice has been field-tested in the United States. A significant number of lines transformed with agronomically useful traits now exist and are being developed for field tests. RFLP maps, that is "road maps" that allow breeders to follow genes, 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 recently established its Collaborative Crop Research Program, which links researchers in less developed countries with U.S. plant scientists in order to strengthen research in selected countries and to focus the work of U.S. scientists on food needs in the developing world. The program is being funded at \$12 to \$15 million for the first six years. While crop engineering is not the sole research tool supported by the program, it plays an extremely important role.

Early in the effort to apply bioengineering to crop improvement, there was great hope placed in the potential to engineer the capacity for nitrogen fixation into crops without it. After the investment of millions of dollars in public and venture capital and many years of research, it has become apparent that the genetic machinery involved in nitrogen fixation by legumes is extremely complex and beyond our current capacity for gene transfer and expression. At some point in the future nitrogen fixation may be transferred to crops such as corn and rice, but such an achievement must be seen as a far-off goal.

It is unlikely that the budgets of these four focused crop biotechnology efforts, taken together, come to more than \$20 million annually. Total agricultural biotechnology research in the developing world may not greatly exceed \$50 million annually.<sup>19</sup> Brazil, China, Egypt, India, and a few other countries have a reasonable base for biotechnology, but most developing countries will find it difficult to develop

useful biotechnology products without sharply directed assistance. Little attention will be paid to crops of importance in the developing world or to the pests, diseases, and stresses that afflict them unless the crops are also important to the more advanced countries. That is, while the gains in fundamental knowledge that apply to all organisms will be available, the programs may not produce applications in the form of transformation techniques, probes, gene promoters, and the like.

### **Potential Contributions of Transgenic Crops**

Transgenic crops have the potential to contribute to increased production and food quality, environmental well-being, and human health.

#### *Potential Applications to Improved Production and Food Quality*

How will the developments of molecular biology contribute to solving the food production problems in developing countries in the years ahead? Contributions may come through two different paths: (1) research in molecular biology directed specifically at food needs in the developing world or (2) "spillover" innovations directed at issues in industrial countries but also beneficial to food production in developing countries.

The preceding section shows that the resources directed at food crop production in developing countries are small, especially when compared with those directed at crops in the industrial world. Still, some important contributions should come from the resources being applied to developing countries. Training of scientists in developing countries under various programs means that there is a small cadre of plant molecular biologists in a number of developing countries. The Rockefeller Foundation's support for rice biotechnology should begin to pay off in two to five years in the form of new varieties available to some Asian farmers. In China varieties produced through anther culture, a form of biotechnology, are now being grown on thousands of hectares by farmers in rural areas near Shanghai. The speed with which varieties get into farmers' hands depends largely on national conditions—the closeness of

links between biotechnologists and plant breeders; the ability of scientists to identify the constraints and the genes that overcome them; the ability of scientists to get those genes into good crop varieties; and the success of plant scientists and others in crafting meaningful biosafety regulations.

It is likely that efforts to improve the rice yield in Asia through biotechnology will result in a production increase of 10 to 25 percent over the next ten years. The increase will come from improved hybrid rice systems in China; in other Asian countries it will come from rice varieties transformed with genes for resistance to pests and diseases. These transformed rice varieties will raise average yields by preventing crop damage, not by increasing yield potential. The reason is simple: few strategies are being pursued to directly raise yield potential because few strategies have been conceived. The use of hybrid rice is one exception. Potential ways to raise yield potential revolve around increasing "sink" size and "source" capacity. Adding to sink size involves increasing the number of grains or the average grain size; increasing source capacity means improving the capacity of the plant to fill these grains with carbohydrate. Both improvements are desired, but there are only a few investigators thinking about how biotechnology might help to achieve these improvements, especially in rice crops. While there is a community of scientists working to understand basic plant biochemistry, including photosynthesis, this work as yet offers no hints about which genes can be manipulated to advantage using the tools of molecular biology and genetic engineering.

Maize yields in developing countries may be affected by biotechnology if genes useful in tropical countries are discovered in the course of the great amount of research on maize under way in the United States. Although most of the maize research is being carried out by private firms, some discoveries may be made available for applications in developing countries either at no cost or at low enough cost to make them commercially feasible. Biotechnology applications beneficial to cassava are further in the future, as are those on the smallholder banana and other crops of importance in the developing world.

Herbicide resistance is potentially the simplest of traits to incorporate into a plant, because application of the herbicide is an ideal way to select a modified individual cell. A population of cells exposed to 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. Thus a number of pressures are at work to ensure that transgenic crops with herbicide resistance are produced. Given that weeds currently constrain crop yields in developing countries, crop yields may rise if herbicide use increases. In addition, proper regulatory activities may lead to increased use of herbicides that are less damaging to the environment (biodegradable herbicides, for example). In impoverished countries cash-poor farmers typically do not have access to such herbicides, especially the expensive ones such as glyphosphate, for which resistance is being engineered. Thus herbicide resistance may not benefit the average farmer in impoverished countries unless the cost of herbicides is reduced. It should be noted that prices are decreasing as patent protection is lost.

Prospects for incorporating pest and disease resistance into developing country crops are more favorable than prospects for increasing yields. Pest and insect problems are much simpler to address, and much of the effort in biotechnology is focused on these problems. Many of the genes that resolve insect and disease problems in temperate crops may also be effective in tropical crops. If they are, problems related to gaining access to the genes and transforming plants with them will remain, because most of the genes have associated intellectual property rights. In one case Monsanto made available to Mexico, without cost, the genes that confer resistance to important potato viruses and trained Mexican scientists in plant transformation and other skills needed to make use of the genes. The transformed potatoes are now being field-tested in Mexico. Monsanto has also worked with USAID and KARI to develop and donate a similar virus control technology to Kenya and Indonesia for virus control in the sweet potato. These cases are, however, exceptional.

Drought is a major problem for nearly all crop plants, and the prospect of a "drought resistance gene" has excited many scientists. However, plant scientists recognize that many traits contribute to drought tolerance or resistance: long, thick roots; thick, waxy leaves; the ability to produce viable pollen when 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 has been made thus far in identifying the genes that control them. Salt tolerance is often discussed along with drought tolerance because salt conditions and drought cause plants to react in similar ways. Unfortunately, some of the genes that confer drought tolerance may be useless for salty conditions and vice versa. Some early workers held that fusing cells of plants tolerant to drought with nontolerant plants would result in a useful combination, but that has not been demonstrated despite considerable effort.

The possibility of increasing the starch content of crops through genetic manipulation that modifies the biosynthetic pathways of the plant is enticing. Some success has been demonstrated in the case of the potato. This success holds out the hope that it may be possible to achieve the goal of a significant increase in production potential in the potato and other root and tuber crops such as cassava, yams, and sweet potatoes.<sup>20</sup>

Prospects for achieving this goal may depend on two factors: (1) the extent to which there are alternative metabolic routes to the same product and (2) the extent to which control of plant metabolism is shared among the component reactions of individual pathways.<sup>21</sup> "There may well be short pathways in plant metabolism where control is dominated by one or two steps, but the current evidence suggests that this is not so for the longer pathways. This conclusion has far-reaching effects on our ability to manipulate plant metabolism."<sup>22</sup>

#### *Potential Applications to Environmental Problems*

Genetic engineering holds out the possibility that plants can be designed to improve human welfare in ways other than by improving crop properties or yields. For example, a biodegradable plastic can be made from the bacterial storage product polyhydroxybutyrate, and the

bacterial enzymes required to convert acetyl-CoA to polyhydroxybutyrate have been expressed in the model plant *Arabidopsis thaliana*. This accomplishment demonstrates the possibility of developing a plant that can accumulate appreciable amounts of polyhydroxybutyrate.<sup>23</sup> The optimization of such a process in a plant that will produce the substance in commercial quantities has not yet been achieved.

At present 80 percent of potato starch is chemically modified after harvest. If starch modification could be tailored in the plant, costs might be lower, and the waste disposal problems associated with chemical modification would be reduced.<sup>24</sup>

The observation that certain plants can grow in soils containing high levels of heavy metals such as nickel or zinc without apparent damage suggests the possibility of deliberately removing toxic substances using plants. Plants with the ability to remove such substances (hyperaccumulators) typically accumulate only a single element and grow slowly. In addition, most have not been cultivated, so their seeds and production techniques are poorly understood. One way around these limitations might be to genetically engineer crop plants to hyperaccumulate toxic substances. Some increased metal tolerance has been obtained in transgenic *Arabidopsis* plants.<sup>25</sup> The use of plants for decontamination of soil, water, and air is still at an early stage of research and development. "No soil has been successfully decontaminated yet by either phytoextraction or phytodegradation."<sup>26</sup>

#### *Potential Applications to Human Health Problems*

As a result of biotechnology, compounds that were previously available only in limited quantities or from exotic plant species or other organisms can now be produced in domesticated crops. It has already proved feasible to produce carbohydrates, fatty acids, high-value pharmaceutical polypeptides, industrial enzymes, and biodegradable plastics.<sup>27</sup> Production of proteins and peptides has been demonstrated, and it has been shown that plants have several potential advantages over microbial fermentation systems. Bacterial fermentation requires significant capital investment and often results in the pro-

duction of insoluble aggregates of the desired material that require resolubilization before use. Plant production of such proteins would avoid the capital investment and would in most cases produce soluble materials. However, the cost involved in extracting and purifying proteins from plants may be significant and may offset lower production costs, although the economics of purifying proteins from plant biomass has not been evaluated extensively.<sup>28</sup> This disadvantage can to some extent be offset by expressing the protein in the seed at a high level.<sup>29</sup>

Plants can potentially be used as the producers of edible vaccines. The hepatitis B surface antigen has been expressed in tobacco, and the feasibility of oral immunization using transgenic potatoes has been demonstrated.<sup>30</sup> The challenges involved in the design of specific vaccines include optimizing the expression of the antigenic proteins, stabilizing the expression of proteins in the post-harvest process, and enhancing the oral immunogenicity of some antigens.<sup>31</sup> There are even greater challenges to developing effective protocols for immunization.

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# Possible Problems

All new technologies must be assessed in terms of benefits and costs. This section outlines a number of potential costs or problems that may be associated with developing and using the new tools of biotechnology in developing countries. Some of the problems associated with biotechnology for crop improvement are not new. Indeed, some of the problems that were faced thirty years ago during the Green Revolution must be addressed once again to safeguard the use of agricultural biotechnology. The new tools of biotechnology give us more power to make positive or negative impacts on the environment than was the case with conventional plant breeding technologies used during the Green Revolution. Thus it is essential that we review critically the potential problems that have been raised by scientists and environmentalists.<sup>1</sup> Our intention here is to present a balanced review of current knowledge concerning risks and problems.

### Gene Flow in Plants: Crops Becoming Weeds

In most groups of plants related species regularly form hybrids, and the transfer of genes between the differentiated populations that such hybridization makes possible is a regular source of enhancement for the populations involved. Thus all white oaks and all black oaks (the two major subdivisions of the genus, including all but a few of the North American species) are capable of forming fertile hybrids. Some of the species and distinct races that have evolved following such hybridization occupy

wide ranges in nature and can be recognized as a result of their distinctive characteristics. The characteristics of corn, wheat, and many other crops were enhanced during the course of their evolution as a result of hybridization with related species or weedy or cultivated strains that were nearby; those related, infertile, and sometimes weedy strains have also been enhanced genetically, in some instances following hybridization with the cultivated crop to which they are related.

In view of these well-known principles, studied for well over fifty years, it is clear that any gene that exists in a cultivated crop or plant, irrespective of how it got there, can be transferred following hybridization to its wild or semidomesticated relatives. The transfer would occur selectively if the gene or genes being transferred enhanced the competitive abilities of the related strains, and the weedy properties of some kinds of plants might be enhanced in particular instances as a result of this process. If so, those new strains might need special attention in controlling such plants, just as the many thousands of weedy strains of various plants that have developed over the history of cultivation need control.

Because most crops, such as corn and cotton, are highly domesticated, it is unlikely that any single gene transfer would enable them to become pernicious weeds. Of greater concern is the potential for less domesticated, self-seeding crops (alfalfa, for example) and commercial tree varieties (pines, for example) to become problems. These plants already have the capacity to survive on their own, and transgenes could

enhance their fitness in the wild. For example, a pine tree engineered for resistance to seed-feeding insects might gain a significant advantage through decreased seed destruction, potentially allowing it to outcompete other indigenous species. If this happened, forest communities could be disrupted.

### **Gene Flow in Plants: From Transgenic Crops to Wild Plants**

Crop varieties are often capable of breeding with the wild species from which they were derived. When the two plant types occur in the same place, it is possible for transgenes, like other genes in the domesticated plant, to move into the wild plants. In some cases these crop relatives are serious weeds (wild rices and Johnson grass, for example). If a wild plant's fitness was enhanced by a transgene, or any other gene, that gave it protection from naturally occurring diseases or pests, the plant could become a worse pest, or it could shift the ecological balance in a natural plant community. Wild relatives of crops suffer from diseases and insect attack, but there are few studies that enable us to predict whether the development of resistance to pests in wild plants would result in significant ecological problems. Weeds often evolve resistance to diseases by natural evolutionary processes. However, in some cases, gene transfer from crops could speed up this process by hundreds of years.

Wild rices are especially important weeds in direct-seeded rice (direct seeding of rice is an agricultural practice that is becoming more widely used in Asia). It has been shown that genes are often naturally transferred between domesticated rice and weedy wild rices. If a herbicide tolerance gene was engineered into a rice cultivar, it would be possible to control the wild rice in commercial rice fields with the herbicide until the wild rice acquired the herbicide tolerance gene from the cultivar. Once the wild rice obtained this gene, the herbicide would become useless. The wild rice would not become a worse weed than it was before genetic engineering as a result of acquiring the herbicide tolerance gene. However, this natural gene transfer would make the investment in the engineering effort much

less sustainable. Therefore, it is important to consider such gene transfer before investing in specific biotechnology projects. Weeds can evolve resistance to some herbicides without gene transfer, but the process takes much longer. For example, herbicides such as glyphosate (Round-Up) from Monsanto are difficult for plants to resist with their normally inherited genes. (It should be noted, however, that the intensive use of glyphosate has led to weed resistance in Australia.)

### **Development of New Viruses from Virus-Containing Transgenic Crops**

Viral diseases are extremely destructive to plant productivity, especially in the tropics. Consequently, the genetic modification of plants to resist viruses has been an important objective of conventional breeding. Over the past decade biotechnology has made possible the more rapid and precise production of individual strains resistant to particular viruses as a result of the ability to move particular genes into specific crop strains. One of the goals of genetic engineering has been to identify novel virus-resistant genes that can be rapidly transferred to many types of crops, thus easing the problems of the plant breeder and meeting the needs of the farmer. As has always been the case with such efforts, the major challenge is to find virus-resistant genes that cannot be overcome easily by the action of natural selection of the virus. Now, however, we have the potential to react more efficiently to this challenge than before.

One potential advantage of genetic engineering is that it may make possible the transfer of multiple genes for disease resistance that affect the disease organism by different mechanisms. In many cases such a transfer would make adaptation by the disease organism more difficult. Engineering multiple genes for disease resistance into crops requires advanced technical effort, and the benefits of such an effort will only be seen years after the varieties are commercialized. Therefore, it is important that genetic engineers be given a mandate to develop genes that will protect crops for extended periods of time.

### *Pathogen-Derived Resistance*

To date the most widely applied genetic engineering technology for controlling plant viruses has been the use of genes derived from the plant viruses themselves. When transferred to plants, a set of genes called viral coat protein genes inhibit replication of the virus. (Other virus-derived genes can have a similar impact when they are transferred to plants in an appropriate manner.)

Transgenes encoding a variety of viral genes have been tested in transgenic plants over the past ten years with a range of effects. Plants that produce viral coat proteins have been tested the most widely, and some of these plants have received approval for commercial sale in the United States and China. In 1995 the U.S. Department of Agriculture proposed a rule that would substitute a notification requirement for the permit requirement now in effect for most field tests of selected genetically engineered crops. If this rule is formalized, researchers will only have to notify the department, not obtain a permit, before field-testing certain genetically engineered plants, including those that express viral coat protein genes. Some have found this proposed rule controversial.<sup>2</sup> The U.S. Environmental Protection Agency also ruled that coat proteins are not pesticidal and are safe for environmental release. The U.S. Food and Drug Administration has approved for sale and consumption foods derived from transgenic plants that contain viral coat proteins.

### *Concerns about Release of Plants Containing Genes Encoding Viral Sequences*

As research and development of plants that exhibit pathogen-derived resistance moved from the lab to the field, several concerns were voiced about the release of plants that encode viral sequences, including the following:

- Virus proteins may trigger allergic reactions if included in foods. This concern has been largely abandoned, in part because many foods are infected with plant viruses and have been consumed for many years without known deleterious effects.

- Virus-resistant plants may have a competitive advantage in the field, and outcrossing with weed species may confer increased competition and weediness. As indicated above, we lack data on how important this problem can be.
- The presence of transgenic viral sequences in large crops would increase the likelihood of creating novel viruses because of recombination between the transgenes and other viruses that infect the plant. While it is known that many crops are simultaneously infected by multiple plant viruses, there are few examples of confirmed genetic recombination between different viruses. And, while there is evidence of recombination between like viruses or virus strains, there is no evidence that this recombination would occur with greater frequency in transgenic plants than in typical situations of virus infection. In conclusion there is little evidence for the contention that virus recombination will cause ecological problems.
- Virus coat proteins produced by transgenic crops could combine with natural viruses and produce more harmful strains. It has been concluded that while such an occurrence is theoretically possible, the risk of it is too low to be considered in assessing the impacts of transgenic crops.
- Virus genes other than coat protein genes could elicit greater safety concerns. Genes encoding ribonucleic acids (RNAs) that do not produce proteins yet provide resistance are likely to receive approval because there is no scientific expectation of risk. However, it is unclear whether or not other genes will receive approval. Viral genes that have the capacity to decrease infection by one virus but increase the chance of infection by another virus will probably not receive approval unless they are mutated and made to act only in a protective manner.

### **Effects of Plant-Produced Insecticides on Unintended Targets**

In terms of plant-produced insecticides the only insecticidal compounds that are currently commercialized are proteins that are naturally pro-

duced by *Bacillus thuringiensis* (Bt). These proteins are highly specific in their toxic effects. One group of these proteins affects only certain species of caterpillars (*lepidoptera*), while others affect only a restricted set of beetle species. None of these proteins has been shown to have a significantly disruptive effect on predators of pest species (beneficial insects). The proteins degrade rapidly when exposed to sunlight and have been shown to degrade even when protected by being inside crop residues. Monsanto presented data to the Environmental Protection Agency that confirm the safety of the protein. Studies with enzymes from the human digestive system indicated that these Bt proteins are quickly digested and are unlikely to cause harmful effects.

### **Ecosystem Damage**

Unfortunately little is known about the flow of genetic information from plants to microorganisms, making it difficult to assess the risk of genes spreading from plants to soil organisms. It is a fact that soil organisms, especially bacteria, are able to take up DNA from their environment and that DNA can persist when bound to soil particles. Although one can speculate about a gene-flow situation in which plant DNA is released from plant material, bound to soil particles, and subsequently taken up by soil bacteria, such a scenario is highly unlikely. Any potential risks of such a transfer can be eliminated by making transgenes that bacteria are unable to use (those with introns, for example). It is even more speculative to consider the possible transfer of genes to soil-dwelling fungi (molds), since gene transfer to fungi is generally much more difficult than gene transfer to bacteria.

### **Assessing the Cost-Benefit Ratio of Genetically Engineered Crops**

Two questions that must be addressed before investing in a project to engineer a crop cultivar are (1) will the gene being transferred serve an important function in the targeted geographical area and (2) how long will the gene continue to serve its function?

### *Will the Gene Being Transferred Serve an Important Function in the Targeted Geographical Area?*

The pests of a specific crop, such as cotton or corn, vary from one geographical region to another. For example, the caterpillars of two insect species, the cotton bollworm and the budworm, are major pests to the cotton grown in the southern United States. A variety of cotton developed by Monsanto contains a specific protein derived from *Bacillus thuringiensis* that is highly toxic to these two closely related pests. In Central America the major insect pest species that affect cotton are the fall armyworm and the boll weevil. Since the toxins in the cotton developed by Monsanto have no impact on these pests, investing in the transfer of these seeds to Central America would be futile. Instead, it would be better to invest resources in finding more appropriate genes that would truly control Central American cotton pests.<sup>3</sup>

A number of companies have engineered corn varieties that tolerate herbicide sprays. At this point the commercial corn varieties that possess herbicide tolerance are developed by crossing a parent corn line that contains the transgene for herbicide resistance with another line that does not contain the gene. Therefore, all of the commercially sold corn seeds contain one copy of the herbicide-resistance gene and are resistant to the herbicide. In the United States farmers buy hybrid corn seed every year and plant it only once so that all of their plants are tolerant of the herbicide spray. While this system works well in the United States and other similar economies, it will not work well in agricultural settings in most developing countries unless changes are made. For example, in El Salvador many farmers buy hybrid corn seed only once every three years, because it is very expensive. The first year they plant the commercial seed, and the next two years they plant the offspring from the plants. Because of genetic segregation in the offspring, only three-quarters of the corn plants in the second and third year have the herbicide-resistance gene, so the farmer kills half of the crop by applying the herbicide. It has proven too difficult for seed companies to put the gene in both parents of the plant. Clearly, an agricul-

tural plan that works in a developed country may not work in a developing country.

It is often said that biotechnology is a transferable technology because "the technology is all in the seeds." It is important to recognize that the interface between seed traits and worldwide crop production is not always simple. As indicated above, sending herbicide-resistant corn seed to El Salvador without educating farmers about the problem of using the second generation seed could lead to immediate economic losses, and it could also lead to rejection of the new technology. Similarly, breeding a corn variety in the United States and then sending it to West Africa would be useless if the corn was resistant to U.S. pests but not to West African pests. It should be noted that corn pests are not even the same in all West African countries, so varieties must be developed by tailoring them to specific problems.

Once a variety is matched with local pest problems, the technology may be transferable simply by supplying the seed, although doing so does not mean that the seed will provide a sustainable solution to the pest problem. There is abundant evidence indicating that pests will overcome genes for pest and disease resistance, regardless of whether the genes have come through biotechnology or classical plant breeding, unless seeds are used properly. Getting farmers to use seeds properly will require educational efforts.

#### *How Long Will the Gene Continue to Serve Its Function?*

Insects, disease-causing organisms, and weeds are known to adapt to most pesticides and crop varieties that contain resistant genes. In some cases adaptation occurs within one or two years. Some insect strains have evolved the ability under laboratory and field conditions to tolerate high concentrations of the toxins derived from the *Bacillus thuringiensis* that are produced by transgenic cotton and corn sold commercially in the United States. Considerable theoretical and empirical research has assessed whether certain insect pests will overcome the effects of transgenic crops that produce these insecticidal proteins. If major crops, such as

corn, cotton, and rice, that produce insecticidal proteins are planted intensively over wide areas, the chance for insect adaptation is high unless care is taken in developing and deploying the insect-resistant varieties.

The U.S. Environmental Protection Agency has put restrictions on the sale of cotton containing *Bacillus thuringiensis* to ensure that every U.S. farm has some fields planted with varieties that do not produce the Bt proteins. These restrictions are an example of the kinds of strategies that can be employed to "conserve resistance." The fields planted with non-Bt-producing varieties act as refuges for individual pests that are susceptible. The insects produced in these refuges will mate with resistant insects emerging from fields where the transgenic varieties are planted, diluting the frequency of insects that are resistant to the Bt proteins and leading to more sustainable resistance. Instituting such practices in developing countries would probably be difficult. Furthermore, the refuge strategy works best if the transgenic variety produces enough Bt protein to kill close to 100 percent of the susceptible insects that feed on it. A variety developed to kill 100 percent of the pest individuals of a species that occurs in Mexican corn may kill only 80 percent of the insects in a Nigerian cornfield. Therefore, attempts to build one transgenic corn type to fit the needs of a number of countries may be misguided.

Adaptation problems similar to those described for insects may affect crops engineered for resistance to disease and tolerance of herbicides. Although there are some types of herbicides, such as glyphosate (Round-Up), that are considered "immune" to weed adaptation, it is not clear that this immunity will hold up when there is intensive use of the herbicide.<sup>4</sup>

When investing in biotechnology for crop protection, it is important to consider the global effectiveness of the protection and how long it will last. The same is true of agriculture in general. Improved strains of any kind of crop or domestic animal, regardless of how the genetic modification was attained, must be carefully managed to be as productive as possible. Integrated systems involving the best and most sustainable practices of soil preparation; the most conservative and appropriate use of water, fertilizers, and pesticides (if pesticides are used);

and the selection of the best and most appropriate strains of a particular crop are the key to success in agriculture. These practices are important to all agricultural systems, and they are necessary for improving systems, regardless of the exact methods used to genetically modify the crop strains being grown.

Investments in new and improved crop strains must also be judged by their global effectiveness, irrespective of how the strains were produced. The Green Revolution succeeded in enhancing productivity in many areas because of the system of cultivation that was built up around the new strains of crops, not solely because of the properties of those strains. The design of plantings has a great deal to do with the longevity of resistance to particular diseases and pests, but design has not always been carefully considered in efforts to introduce genetically engineered strains or other novel strains. The design of plantings may need special attention in developing countries with respect to the particular conditions found there.

As mentioned above, biotechnologies other than bioengineering can be used to improve agriculture in developing countries. But use of such technologies can also have drawbacks for devel-

oping countries. For example, tissue culture can be used to produce disease-free plants and to help increase the productivity of farms in developing countries. But tissue culture can also be used to shift the production center for specialty agricultural products from developing to industrial countries. Vanilla is typically considered a tropical product, but recent work with tissue culture allows its production in the laboratory. If such innovations in tissue culture proliferate, it is possible that other tropical products will be manufactured in the laboratory as well.

### Notes

1. A. A. Snow and P. M. Palma, "Commercialization of Transgenic Plants: Potential Ecological Risks," *BioScience* 47 (February 1997).

2. Personal communication.

3. N. Strizhov and others, "A Synthetic cryIC Gene, Encoding a *Bacillus Thuringiensis* D-Endotoxin, Confers *Spodoptera* Resistance in Alfalfa and Tobacco," in *Proceedings of the National Academy of Sciences USA* (forthcoming).

4. J. Gressel, "Fewer Constraints Than Proclaimed to the Evolution of Glyphosate-Resistant Weeds," *Resistant Pest Management* 8 (1996): 2-5; B. Sindel, "Glyphosate Resistance Discovered in Annual Ryegrass," *Resistant Pest Management* 8 (1996): 5-6.

# Conclusions and Recommendations

**T**he panel's recommendations to the World Bank are based on its members' belief that urgent priority must be assigned to the expansion of agriculture and to increased production of food in the developing world. It is critically important that increases in food production outpace population growth. Damaging agricultural practices must be replaced with lower-impact, sustainable activities so that the global capacity to produce food does not decline. Only by these means will it prove possible to lessen hunger and improve food security in the poorest nations in the years ahead.

Because transgenic technology is so powerful, it has the ability to make significant positive or negative changes in agriculture. Transgenic crops are not in principle more injurious to the environment than traditionally bred crops. This report has outlined a number of criteria that can be used to determine whether a specific biotechnology program is likely to enhance or detract from ecologically sound crop production. Transgenic crops that are developed and used wisely can be very helpful, and may prove essential, to world food production and agricultural sustainability. Biotechnology can certainly be an ally to those developing integrated pest management (IPM) and integrated crop management (ICM) systems.

The recommendations to the World Bank follow.

### Support of Developing World Science

*The Bank should direct attention to the need for liaison with and support of the developing world's agri-*

*cultural science community.*

It is of the greatest importance to the development of sound agriculture, based on the best environmental principles, to enhance the capabilities of science and scientists in the developing world. A specific and urgent need is the training of developing world scientists in biotechnology methods so that each nation will have a cadre of scientists to assist it in setting and implementing its own policies on biotechnology research and biosafety.

The education of farmers can be greatly facilitated with the aid of scientists from their own nations. These scientists can contribute to the success of newly introduced crop strains and help to implement early warning systems to identify any troubles that arise during the introduction of new crops or new agricultural methods.

### Research Programs

*The Bank should identify and support high-quality research programs whose aim is to exploit the favorable potential of genetic engineering for improving the lot of the developing world.*

As noted earlier in this report, not all of the research in progress in the industrial nations will, even if successful, prove beneficial to the developing world. Research should be planned so that key needs are met. Much of the necessary research will need to be done in advanced laboratories in industrial countries in conjunction with laboratories in developing countries. Research priorities should focus on promoting sustainable agriculture and higher yields in the developing world as well as on decreasing the

variation in food production arising from, for example, environmental stresses.

Variance in production can result in food shortages with numerous attendant complications. Crops with resistance to insects and diseases, including crops developed by genetic modification, can decrease production variance if the crops are developed and deployed in ways that minimize the ability of pests and diseases to overcome the resistance factors in the crop. A poorly conceived strategy for developing and deploying crops can have the opposite effect if pests or diseases adapt to resistant cultivars. If farmers are taught to depend solely on a crop's ability to ward off pests and diseases, the farmers will not be prepared to use alternative means of control when pests become adapted to the resistance factors in the crop.

### **Surveillance and Regulation**

*The Bank should support the implementation of formal, national regulatory structures in its client nations by seeing to it that these structures retain their vigor and effectiveness through the years and by providing scientific and technical support to the client nations as requested.*

Effective regulatory structures will prove critical should problems arise during the introduction of transgenic crops or, indeed, of other tools of industrialized agriculture, including chemical inputs, some of which may be promoted in conjunction with genetically engineered herbicide-tolerant crops. These tools can all pose problems for developing countries. Effective, comprehensive regulatory structures appear to exist in few nations, if any, including the United States. To provide the basis for a strong national regulatory structure, there must be a designated agency with a clear mandate to protect the environment and the economy from risks associated with the uncritical application of new methods, including inappropriate new strains of crops or animals that may pose special risks for the environment. The agency must have the technical capacity to develop competent risk assessment and the power to enforce its decisions.

*The Bank should support, in each developing country, the deployment of an early warning system*

*to identify any troubles that may arise and to introduce improvements in adapting new strains.*

As an early warning system helped to identify troubles, it would also spot unexpected success, so that gains could be exploited and duplicated elsewhere. The system would also provide feedback to speed up and optimize the introduction of new plant varieties.

### **Investment in International Agricultural Research Centers**

*The Bank should increase its support of research in biotechnology and related areas at international agricultural research centers because these centers are in the best position to ensure that high-quality, environmentally sustainable agricultural products and processes are developed and transferred to developing countries.*

International agricultural research centers are well placed to assist in the implementation of many of our recommendations. Investment in biotechnology research at these centers is marginally low. Although some of the centers have healthy but small programs in place, most of them lack the infrastructure and personnel needed to conduct high-quality biotechnology research. The Bank should determine how best to invest in infrastructure and personnel at each site. The Bank should adopt a broad perspective on biotechnology research that includes support for marker-assisted breeding, development of transgenic plants, development of molecular-based but farmer-friendly diagnostics, and genetic analysis of crop pests and pathogens. Research should emphasize development of agricultural products and processes that are unlikely to be provided by the private sector, such as those that would alleviate problems specific to subsistence farmers. Any increased investment in new agricultural technology must be accompanied by significant investment in ecological and sociological research to ensure that new products and processes support safe and sustainable food production.

In implementing Bank support for international agricultural research centers, two matters are important. The first is for the Bank to ensure that leaders of research organizations are aware of the potential and importance of

supporting biotechnology research. The second is for the Bank to ensure that the recommendations—to focus on liaison and to identify and support high-quality research—are adopted in the implementation of a program of enhanced support for international agricultural research centers. Increases in funding for agricultural biotechnology should involve cooperation with scientists from developed countries, and any facilities that may be built at the centers should match the scientific capabilities that are to be maintained over the long term.

### **The Agricultural Challenge**

*The Bank should continue to give high priority to all aspects of increasing agricultural productivity in the developing world while encouraging the necessary transition to sustainable methods.*

While genetically engineered crops can play an important role in meeting the goal of improved food security, their contribution alone will not suffice. Their use must be accompanied by numerous other actions, as we have noted in preceding sections of this report. These actions include:

- Increasing priority on conventional plant breeding and farming practices

- Ensuring that adequate energy and water become available and that procedures for their efficient use are made known and adopted
- Ensuring the introduction of modern means of controlling pests, including the use of integrated pest management systems, safe chemicals, and resistant crops
- Supporting the transition to sustainable activities and the reduction of waste and loss in all elements of the agriculture enterprise
- Providing the necessary education to farmers so that they can implement the array of new techniques that are needed (integrated pest management, for example)
- Ensuring that the changes in agriculture will provide the employment opportunities that will be needed in the developing world.

The scale and importance of the challenge that the Bank faces in the agricultural sector are formidable. We have concluded that the Bank should establish a permanent technical and scientific advisory group to deal broadly with the goal of improving food security while ensuring the transition to sustainable agricultural practices. The group should deal with all the elements that comprise a successful program and provide the required liaison to the scientific communities in the target nations.



# Integrated Intensive Farming Systems

### **Intensive Farming**

China and India, as well as numerous other developing nations, must achieve the triple goals of more food, more income, and more livelihoods from their land and water resources. One approach that can be adopted is the integrated intensive farming systems methodology (IIFS).

The M. S. Swaminathan Research Foundation has designed a bio-village program to convert IIFS from a concept into a field-level reality. By making living organisms both the agents and beneficiaries of development, the bio-village serves as a model for human-centered development. The pillars of the IIFS methodology follow.

### **Soil Health Care**

Soil health care is fundamental to sustainable intensification of agriculture. The IIFS approach affords the opportunity to include stem-nodulating legumes such as *Sesbania rostrata* in the farming system and to incorporate *Azolla*, or blue-green algae, and other sources of symbiotic and nonsymbiotic nitrogen fixation. Vermiculture constitutes an essential component of IIFS. IIFS farmers maintain a soil health card to monitor the impact of farming systems on the physical, chemical, and microbiological components of soil fertility.

### **Water Harvesting, Conservation, and Management**

IIFS farm families include in their agronomic practices measures to harvest and conserve rain-

water so that it can be used in conjunction with other sources of water. Where water is the major constraint, technologies that can help to optimize income and jobs from every liter of water must be chosen and adopted. Maximum emphasis should be placed on efficient on-farm water use and on the use of techniques such as drip irrigation to help optimize the benefits from the available water.

### **Crop and Pest Management**

Integrated nutrient supply (INS) and integrated pest management (IPM) systems form important components of IIFS. The precise composition of the INS and the IPM systems should be chosen on the basis of the farming system and the agro-ecological and soil conditions of the area. Computer-aided extension systems should be developed to provide farm families with timely and precise information on all aspects of land, water, pest, and postharvest management.

### **Energy Management**

Energy is an important and essential input. In addition to the energy-efficient systems of land, water, and pest management described above, every effort should be made to harness biogas, biomass, solar, and wind energies to the maximum extent possible. Solar and wind energy can be used in hybrid combinations with biogas for farm activities such as pumping water and drying grains and other agricultural produce.

## Postharvest Management

IIFS farmers should not only adopt the best available threshing, storage, and processing measures, but should also try to produce value-added products from every part of the plant or animal. Postharvest technology assumes particular importance in the case of perishable commodities such as fruits, vegetables, milk, meat, eggs, fish, and other animal products. A mismatch between production and postharvest technologies adversely affects both producers and consumers. As this report has noted, growing urbanization leads to a diversification of food habits. This diversification will increase demand for animal products and processed food. Agro-processing industries can be promoted on the basis of an assessment of consumer demand. Such food-processing industries should be promoted in villages in order to increase employment opportunities for rural youth.

Investment in sanitary and phyto-sanitary measures is important to providing quality food for domestic consumers and for export. To assist the spread of IIFS, governments should make major investments in storage facilities, roads, communication, and sanitary and phyto-sanitary measures.

## Choice of Crops and Other Components of the Farming System

In IIFS it is important to give careful consideration to the composition of the farming system. Soil conditions, water availability, agro-climatic features, home needs, and above all, marketing opportunities have to determine the choice of crops, farm animals, and aquaculture systems. Small and large ruminants have a particular advantage among farm animals since they can live largely on crop biomass. IIFS farming has to be based on both land-saving agriculture and grain-saving animal husbandry.

## Information, Skills, Organization, and Management

To succeed, IIFS farms need a meaningful and effective information and skill empowerment system. Decentralized production systems have to be supported by a few key centralized services, such as the supply of seeds, biopesticides, and diagnostic and control methods for plant and animal diseases. Ideally, an "information shop" should be set up by trained local youth in order to give farm families timely information on meteorological, management, and marketing factors. Organization and management are key elements to success, and depending on the area and farming system, steps have to be taken to provide to small producers advantages of scale in processing and marketing. IIFS farming is best developed through participatory research between scientists and farm families. This approach helps to ensure economic viability, environmental sustainability, and social and gender equity in IIFS villages. The starting point is to learn from families who have already developed successful IIFS procedures.

It should be emphasized that IIFS will succeed only if centered on humans; a mere technology-driven program will not work. The essence of IIFS is the symbiotic partnership between farming families and their natural resource endowments of land, water, forests, flora, fauna, and sunlight. Without appropriate public policy support in areas such as land reform, security of tenure, rural infrastructure, input and output pricing and marketing, small farm families will find it difficult to adopt IIFS.

The eco-technologies and public policy measures needed to make IIFS a mass movement should receive concurrent attention. The program will fail if it is based solely on a technological quick-fix approach. On the other hand the IIFS program can trigger an "ever-green revolution" if mutually reinforcing packages of technology, training, techno-infrastructure, and trade are introduced.

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