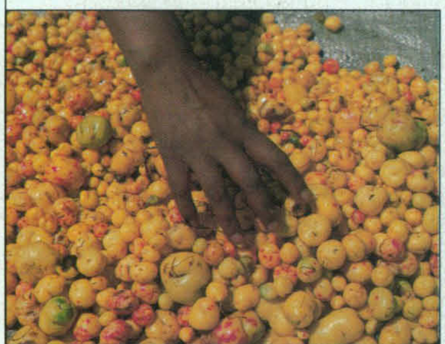
The Plant Revolution

The initial phase of a revolution in agriculture has already occurred. Large areas of genetically modified (GM) crops of soybeans, corn, cotton, and canola have been successfully grown in the Western Hemisphere. In the United States in 1999, of the total of 72 million acres (29 million hectares) planted with soybeans, half were planted with GM herbicide-resistant seeds. When herbicide-resistant seeds were used, weeds were easily controlled, less tillage was needed, and soil erosion was minimized. Worldwide in 1999, about 28 million hectares of transgenic plants are being grown. Some experts predict that this area will be tripled in the next 5 years.

During this early phase of the plant revolution, the benefits of plant engineering have been largely confined to farmers. Currently, U.S. companies that are active in transgenic plant research will spend far more money on R&D than they will receive as their share of profits from modified seeds, sales of which will amount to only $1.5 billion. Apparently most of the agrichemical companies, including those in Europe, envision a far more lucrative future when the plant revolution matures further. One possibility is the $500 billion market for foods in the United States. There is increasing evidence that transgenics can produce healthier food. Another opportunity is to use plants as chemical factories. The next major phase of the plant revolution will emphasize the engineering of desirable traits in plants; traits that are readily apparent to the consumer.

This issue of *Science* includes a sampling of the evolving status of the plant revolution and examples of the many opportunities for important research that genetic modification promises. Mazur *et al.* (p. 372) portray some of the achievements of staff at the DuPont Co. in modifying output traits in plants. For about 15 years, DuPont scientists and engineers have been engaged in intense efforts to control the kinds of chemicals produced by plants. They have enjoyed success and have been able to channel plant metabolism into producing industrial feedstocks and pharmaceutical and nutraceutical products. The selection of superior strains and the conventional breeding of soybeans have led to lines with reduced levels of antinutritional oligosaccharides, stachyose, raffinose, and galactose. Modification of the genome of soybeans to produce desirable fats is leading to healthier foods and to useful industrial chemicals. The common varieties of soybean seeds contain mainly polyunsaturated fatty acids that decompose when heated. In order to achieve more stability and a higher melting point, industrial hydrogenation has been used, although it creates unhealthy trans fatty acids. A desirable objective therefore was to develop soybean seeds that mainly produce the monounsaturated fatty acid oleic acid. Mazur *et al.* report raising the relative level of this substance in seeds from 25% to 85%. Large areas of these strains of soybeans are now under cultivation. Another effort that succeeded was to use soybean plants to produce vernolic acid and ricinoleic acid, derivatives of oleic acid that are used as hardeners in paints and plastics. The necessary genes were derived from Vernonia and castor bean seeds and were transferred into the soybean genomes.



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The authors also describe a method for increasing the energy content of corn, much of which is devoted to animal feed. Varieties developed at the University of Illinois had high oil content but poor agronomic characteristics. To deal with this problem, the TopCross grain production system was developed. A male, fertile, high-oil corn variety is interplanted at low den-

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sity with a male, sterile elite hybrid. The system has been used successfully on hundreds of thousands of acres.

An important facet of the DuPont development process is functionality assessment to measure end-use attributes, thus increasing the likelihood that value-added traits will be found and used in multiple products. Such tests demonstrated that flour and oil from high-oleate soybeans have improved heat and shelf-life stability in foods. The same high-oleic oil is useful as an industrial lubricant.

DellaPenna (p. 375) portrays some of the needs for and experimental approaches to attaining healthier levels of micronutrients in foods. Most people in the developed countries have more than adequate supplies of macronutrient carbohydrates, proteins, and fats. Essential micronutrients, including 17 minerals and 15 vitamins, are also readily available in quantities sufficient to alleviate diseases of deficiency. However, in developing countries large numbers of people exist on simple diets that are poor sources of macronutrients and of many micronutrients. The food of over 800 million people does not contain sufficient macronutrients, and micronutrient deficiencies are even more prevalent. A deplorable fact is that 250 million children are at risk for vitamin A deficiency. A lack of this vitamin leads to learning disabilities, and each year 500,000 children suffer irreversible blindness from vitamin A deficiency.

In addition to the usual macro- and micronutrients, plants synthesize 80,000 other substances. Many of these phytochemicals have effects on human health. Some appear to be associated with lower morbidity in adult life. The exact chemical compounds are largely unknown, but groups of chemicals, including glucosinolates and phytoestrogens, have been identified as being helpful. As more data become available concerning desirable micronutrients, the goal of increasing their content in foods will become compelling. Genes for synthesizing these substances will be identified and incorporated in the various food crops. DellaPenna mentions his own recent success in increasing the expression of vitamin E ninefold in *Arabidopsis* seed oil.

The Somervilles (p. 380) provide their estimate of future developments in plant biology. They describe how new experimental tools and bioinformatics will greatly accelerate the acquisition of knowledge about the function of all plant genes. Soon the genomes of *Arabidopsis* and rice will be completely sequenced. The genomes of wheat, maize, sorghum, millet, and other cereals can be deciphered on the basis of their similarity to the rice genome because of extensive synteny among the cereal genomes. Extensive partial cDNA sequence information will become available for a majority of the genes of many plant species. As genes become associated with functions or traits in one plant, it will usually be possible to use a database search to identify orthologs responsible for the trait in other plant species.

One of the most important experimental approaches for discovering the function of genes is DNA microarrays. From them, extensive databases of quantitative information will be obtained about the degree to which genes respond to pathogens, pests, drought, cold, salt, growth regulators, herbicides, and other agrichemicals. These databases of gene expression will provide novel insights into the genes that control complex responses, and they will also create an opportunity to assign functional information to genes of otherwise unknown function.

A world of farms. Terraced hillsides in Nepal (*top*), fields and hedgerows in England (*center*), and a U.S. corn and dairy farm (*bottom*).

CREDITS: (TOP TO BOTTOM) CRAIG LOVELL; MICHAEL HART/FPG; LARRY LEFEVER/GRANT HEILMAN

One of the major advances could be the discovery of the mechanisms of hybrid vigor. The authors speculate that hybrids will exhibit substantial differences in the expression of clusters of functionally related genes and that different hybrids will have different patterns of expression. If this proves to be the case, it may be possible to progress toward more predictive development of heterotic hybrids.

The provocative suggestion that clusters of genes might be transferred between plant species opens a new set of opportunities. For instance, the transfer of dozens of seed storage protein genes may be desirable in order to tailor the amino acid content of seeds.

Serageldin (p. 387) argues that the developed countries should more vigorously address the needs of poor people in the less developed countries (LDCs). Improvements in food supplies, rural health, rural roads, education, and credit institutions are needed. A world population increase of about 86 million per year is occurring, mainly in the poorest countries. Future growth of food supplies there will have to come from existing land. Serageldin mentions the possibility of harnessing the genetic revolution to benefit the poor of the LDCs. However, he lists a host of ill effects that could arise in LDCs from successful genetic manipulation of crops by U.S. companies. He ends with suggestions for ameliorating some of the conflicts between north and south over patents and proprietary information.

Gaskell *et al.* (p. 384) explore the contrasting attitudes toward genetically modified foods in Europe and the United States. Much of their data is based on surveys conducted in late 1996 and 1997, although their results are apparently still valid today. The authors cite many interesting reasons for the fear and antagonism toward GM foods in Europe. One is a lack of faith in official regulatory bodies. Other organizations were deemed more trustworthy; only 4% of those surveyed chose their governments as reliable sources of GM information. In contrast, in the United States the U.S. Department of Agriculture and the Food and Drug Administration were regarded as highly believable.

The plant revolution is proceeding. It is being propelled by the skillful application of enormous resources of brains, money, and technology. Soon much healthier foods will be available in the United States and some other countries. The revolution has brought with it global social and economic tensions that may persist. In the longer term, plants will provide useful renewable answers to the inevitable depletion of petroleum and its products.

—PHILIP H. ABELSON AND PAMELA J. HINES