Biotechnology in Agriculture and the Environment: Benefits and Risks

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Technological advances in biotechnology, including genetic engineering, have enabled transfer of genetic traits both within species and between entirely different plant and animal species. Currently, biotechnology techniques are being used in various fields, including agriculture, veterinary medicine, pharmaceutical development, forestry, energy conservation, and waste treatment (BIO 1990). These techniques, if applied responsibly, have the potential to increase productivity in crops and livestock, control pests, produce new food and fiber crops, and develop effective medicines (Paoletti and Pimentel 1996). Potential environmental and economic benefits from biotechnology include the reduction of fossil fuel in agriculture and forestry through improved nutrient availability in crops and livestock, use of fewer artificial inputs (e.g., synthetic nitrogen fertilizers, insecticides, and fungicides), and more cost-effective and environmentally friendly waste management practices, such as bioremediation.

If realized, these improvements will help protect ecological systems by reducing habitat degradation (Paoletti and Pimentel 1996). In addition, some of the biotechnology techniques should improve the economics of agricultural and forestry production systems. Although genetic engineering can be expected to provide major benefits to agriculture and the environment, risks with the use of this technology should also be recognized. In this chapter, we assess the environmental, health, and socioeconomic benefits and risks of biotechnology, including genetic engineering, in agricultural systems.
DISEASE-RESISTANT CROPS

Engineering Virus-Resistance in Crops

Resistance against crop disease in plants, caused by viruses, bacteria, and fungi is now being explored through biotechnology and genetic engineering techniques as a way to reduce the loss of crops (Moffat 1992; Gasser and Fraley 1992). Because viruses in the field cannot easily be treated, the production of genetically engineered, virus-resistant crops is agriculturally significant (Mannion 1995). In addition, few antibacterial chemicals are available to control bacterial diseases (Schroth and McCain 1991). It has been estimated that viruses, bacteria, and fungi are collectively responsible for significant crop losses estimated at 12%, or nine hundred million tons, of preharvest yield worldwide (Cramer 1967; Krimsky and Wrubel 1996).

More than 350 field tests of genetically engineered disease-resistant plants have been approved in the United States since 1987, and the majority of these have been created to produce disease-resistant, genetically-engineered crops impervious to viral infections (Krimsky and Wrubel 1996). Success in engineering virus resistance in tobacco, alfalfa, potato, cucumber (Cucumis sativus), melon (Cucumis melo), alfalfa, and tomato plants have been reported by Coozzo et al. (1988), Hill et al. (1991), Truve et al. (1993), Gonsalves et al. (1992), Dong et al. (1991), and Xue et al. (1994), respectively. (See Table 1.)

Field trials with tobacco containing the gene from the mosaic virus for the production of the coat protein have shown that resistance can be transgenically induced. For example, in China, field trials of tobacco that contains the tobacco mosaic virus and tomatoes with cucumber mosaic virus are under way (Chen and Gu 1993). Efforts are also being aimed at improving the quality of rice because of its importance as a staple crop in this region. In Japan, a method for producing fertile transgenic rice plants using an electroporation system has been developed (Shimamoto et al. 1989). Transgenic rice plants expressing the rice stripe virus-coat protein (RSV-CP) have been developed to fight the rice stripe virus, one of the major viruses of rice plants in Japan, Korea, China, and Taiwan (Hayakawa et al. 1992).

The findings of a 3-year biosafety study of ecological risks have demonstrated that expressing the introduced gene (RSV-CP) in a japonica rice variety (Kinukikari) resulted in transgenic rice plants that did not: (1) affect morphological and ecological traits with the exception of some somaclonal variations, (2) hybridize with closely grown rice plants, (3) exhibit the tendency to become weeds, (4) produce any detectable toxic substances, and (5) have any observable effects on subsequent cultivation, microorganisms in soil, insects in folklore, or on surrounding plants (Yahiro et al. 1994). However, these results will need to be followed up with longer-term biosafety assessment in the future.

In the United States, squash and the papaya are two of the more recent models of crop engineering for virus resistance. In 1994, the genetically engineered, virus-resistant squash developed by Asgrow seed company for resistance to zucchini yellow mosaic virus (ZYMV) and watermelon mosaic virus II (WMV II) was one of the first

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<thead>
<tr>
<th>Crop</th>
<th>Disease(s)</th>
<th>Research organization</th>
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<tbody>
<tr>
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<td>Tomatoes</td>
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Source: Krimsky and Wrubel 1996.
genetically engineered crops commercialized in the United States. (Biotechnology Information Center 1996). Researchers have also developed two genetically engineered papaya lines by utilizing RNA techniques to isolate and clone a papaya ringspot virus (PRV) that encodes for the production of the viral coat protein (Fitch et al. 1992). Papaya, one of the three largest crops in Hawaii, has been decimated in recent years by PRV. Hawaiian papaya growers believe these two lines of genetically engineered, disease resistant papaya could save the $45 million Hawaiian papaya industry from extinction (McCandless 1996). However, it should be noted that, although the mild strain of PRV displayed excellent resistance to PRV isolates from Hawaii, it showed only moderate to no protection to isolates from different geographic regions (e.g., Bahamas, Mexico, Florida, Australia, China, Guam, Brazil, Thailand, and Ecuador) (Tennant et al. 1994; Gonsalves et al. 1994).

**Engineering Bacterial and Fungi Resistance in Crops**

Harms (1992), who has reviewed recent developments in the production of resistance to fungal and bacterial diseases via genetic engineering points out that, although there has been much research on how to incorporate such resistance into crop plants, few improvements have been made in this area. Chen and Gu (1993) have described efforts that are being made to combat bacterial blight, which can reduce rice yields by as much as 10%, through genetic engineering.

Developing disease-resistant crops should also receive high priority secondary to the large amounts of fungicides that are currently applied to fruit and vegetable crops (Pimentel et al. 1993). Aspinell et al. (1994) reported that in 1993 131 million pounds of pesticidal active ingredient was applied at a cost of $84 million. Fungicides are sometimes harmful to beneficial insects and toxic to earthworms and many other beneficial soil biota (Edwards and Bohlen 1992; Paoletti et al. 1988, 1991). The number and activity of these soil biota are important in maintaining soil fertility over time because they recycle nutrients in organic matter and aid in water percolation and soil aeration (Crossley et al. 1992). Furthermore, fungicides rank highest for carcinogenicity of all pesticides applied to agriculture and account for approximately 70% of human health problems associated with pesticide use (NAS 1987).

One way to reduce crop losses to fungi and the external application of fungicides is to introduce genes that encode proteins with antifungal properties into crop plants. Several genes have been identified so far in fungi, bacteria, and plants that are effective for the engineering of resistance to fungi based on their ability to produce enzymes, such as chitinase, that attack the cell wall of fungi. Transgenic tobacco plants with a chitinase gene from beans produced elevated levels of chitinase in roots and leaves compared with control plants in greenhouse experiments. Both experimental and control plants were grown in soil inoculated with the fungal pathogen *Rhizoctonia solani*. A positive association was also found between the level of chitinase expressed in the experimental plants and survival (Broglio et al. 1991). Broglio et al. (1993) and Lin et al. (1995) also reported some success has been achieved with engineering resistance to the stem rot pathogen (*Rhizoctonia solani*) in oilseed rape or canola (*Brassica napus*) and rice, respectively. The engineering of resistance to the fungus *Fusarium oxysporum* in the tomato has also been successful (Van den Elzen 1993).

**Risks**

**Creation of New Weeds**

In terms of risks, it has been proposed that large-scale cultivation of plants expressing viral and bacterial genes could lead to novel ecological risks. The most significant ecological risk would be gene transfer via pollination from cultivated crops to wild relatives. For example, it has been postulated that the virus-resistant squash commercialized in 1994 could transfer its newly acquired virus-resistance genes to wild squash (*Cucurbita pepo*), which is native to the southern United States, where it is an agricultural weed. If the virus-resistance genes were to spread, newly disease-resistant wild squash could become a harder, more abundant weed. Moreover, because the United States is the origin for squash, changes in the genetic make-up of wild squash could lessen its value to squash breeders (Goldburg 1995).

Another area of concern is the production of virus-resistant sugar beets, which is likely to result in exchange of genes between cultivated and wild populations of beet (*Beta vulgaris L.*) because production areas contain wild or weedy beet populations, or both, separated by only a few kilometers. A genetic exchange could take place owing to wind pollination, biotic pollination, or the common gynoeceum of wild beets (Beutin et al. 1987; Cuguen 1994). A genetic introgression from seed beet to wild beet populations has already been observed in Europe (Santoni and Berville 1992).

**Viruses that Infect New Hosts**

Some plant pathologists also hypothesize that development of virus-resistant crops may allow viruses to infect new hosts through transencapsulation. This may be especially important for certain viruses (e.g., luteoviruses) for which possible heterologous encapsidation of other viral RNAs with the expressed coat protein is known to occur naturally. With other viruses, such as the PRV, risk of heteroencapsulation is thought to be minimal because the papaya itself is infected by very few viruses (Gonsalves et al. 1994).

**Creation of New Viruses**

Virus-resistant crops may also lead to the creation of new viruses through an exchange of genetic material or recombination between RNA virus genomes. Recombination between RNA virus genomes requires infection of the same host cell with two or more viruses. Several authors have pointed out that recombination may also occur in
genetically engineered plants expressing viral sequences on infection with a single virus and that large-scale cultivation of such plants may lead to increased possibilities of combinations (Hull 1990; Palukaitis 1991; de Zeeven 1991; Tepefer 1993). It has recently been shown that an RNA transcripted from a transgene can recombine with an infecting virus to produce highly virulent new viruses (Greene and Allison 1994). An overall strategy of risk assessment utilizing an incremental approach entails: (1) identifying potential hazards, (2) determining frequency of recombination between homologous but nonidentical sequences, and (3) determining whether such recombinants can have selective advantage (Tepefer et al. 1994). Fernandez-Cuartero et al. (1994) have already demonstrated that, even though a particular pseudorecombinant strain was at a competitive disadvantage relative to a parent cucumber mosaic virus (CMV) strain, a spontaneous recombinant that arose from the pseudorecombinant (resulting from pseudorecombination or the situation in which gene components of one virus are exchanged with the proteins of another coat) had enhanced fitness relative to either of the other original strains.

HERBICIDE-RESISTANT CROPS (HRCs)

At the moment at least 4 engineered crops for target herbicide resistance are on the market, and 13 among the key crops in world production have been extensively tested in field trials (Table 2). In addition, some crops (e.g., corn) are being engineered to contain both herbicide (Glyphosate) and insecticide-resistance (BT δ-endotoxin) (Gene Exchange 1997). The potential benefits and risks of herbicide-resistant crops (HRCs) are discussed in this section.

Potential Benefits Associated with the Use of HRCs

**Possible Reduced Use of Herbicides**

Proponents have argued that reduction of herbicides adopted for HRC crops occurs primarily because these "new" herbicides are needed in lower doses (if compared for instance with atrazine, 2,4-D, and alachlor) and are applied later in crops, post-emergence. However, higher resistance of the crop to the target herbicide would, in practice, suggest to the farmer to adopt a higher rate than advised to ensure that all weeds are burned in one tractor trip with the targeted broad spectrum herbicide (Pimentel and Paoletti 1996).

**Improved Integrated Pest Management (IPM)**

Integrated pest management IPM could benefit from some HRCs if alternative non-chemical methods were applied first to control weeds and the target herbicide were used later, only when and where the threshold of weeds is surpassed, in postemergence
Sulfonylureas and imidazolinones, to be targeted in HRC crops, are particularly prone to rapid evolution of resistant weeds and have already resulted in several cases of resistance (LeBaron and McFarland 1990; Wrubel and Gressel 1994). Extensive adoption of HRCs will increase the acreage and surface treated, thereby exacerbating the resistance problems (Krimsky and Wrubel 1996).

Environmental Risks

Even if less environmentally persistent than previous herbicides (e.g., Alachor, 2,4-D, atrazine), the “environmentally friendly” HRCs have, as do most chemical pesticides, consistent or severe environmental effects (Dekker and Comstock 1992).

Bromoxynil (Commercial Name: Buctril)

Bromoxynil has been targeted in HRC cotton by Calgene and Monsanto (Table 2). This herbicide has traditionally been used in winter cereals, cotton, corn, sugarbeets, and onions to control large-leaf weeds. Drift has been observed that has resulted in damage to nearby grapes, cherries, alfalfa, and roses (Al Khaib et al. 1992). In addition, leguminous plants can be very sensitive to this herbicide (Abd Alla and Omar 1993), and potatoes can be damaged as well. Consistent residues over the accepted standards have been detected in soil and ground water (Miller et al. 1995) and as fallout (Waite et al. 1995). Rodents tested have demonstrated some mutagenic responses (Rogers et al. 1995). Stafilin beetles have been shown to have reduced survival and egg production at suggested dosages (Samsoe-Petersen 1995). Crustaceans (Daphnia magna) have also been severely affected (Buhl et al. 1993).

Glufosinate/Bialaphos (Commercial Name: Basta)

Many crops have been modified for this herbicide-resistance PAT (phosphinothricin acetyl transferase) gene, which has been introduced into alfalfa, corn, barley, wheat, rice, canola, peanuts, soybeans, sorghum, tomatoes, and sugar beets (Table 2). Turfgrass (Agrostis stolonifera) and other components have been engineered for resistance but need appropriate environmental risk assessment before being marketed (Lee 1996). This herbicide has been on the market since 1984 as a synthetic development of a natural pathogen of Streptomyces viridochromogenes (Charudattan et al. 1996; Duke and Abbott 1995). The amount of active ingredient used is 200–900 g/ha postemergence on the engineered plants (AgriEvo 1996).

Although detrimental effects on users and consumers seem unlikely under recommended doses (Hacket et al. 1994), toxic effects on humans and animals have been reported (Cox 1996). For example, the Basta surfactant (sodium polyoxylene alkyl ether sulfate) has been shown to have strong vasodilative effects in humans and cardiostimulative effects in rats (Koyama et al. 1997). Treated mice embryos exhibited specific morphological defects (Watanabe and Iwase 1996).
Imidazolinone (Commercial Name: Imazethapyr)

Imidazolinone is applied at low doses (38–50 g/ha) in beans and soybeans postemergence (Burnside et al. 1994; Perucci and Scarpioni 1994). It has been observed that, at the field rate of 50 g/ha, there is no effect in laboratory and field microbial biomass. However, higher doses induce catalase and hydrolase activity and increase the risk for monocultural practices (Perucci and Scarpioni 1994) and reduced mycelial growth in Sclerotinia trifoliorum (Reichard et al. 1997).

Sulfonyleurea (Commercial Name: Safari)

Sulfonyleurea is used as a herbiocide on wheat, barley, sugarbeets, cotton, maize, potatoes, and soybeans postemergence. Drift from very low amounts (5–30 g/ha) can damage cultures, and potential losses may result in several crops, wild plants, and nontarget invertebrates (Cox 1992).

Glyphosate (Commercial Name: Roundup)

Most HRCs have been engineered for glyphosate resistance. Although adverse effects of herbiocide-resistant soybeans have not been observed on feeding animals such as cows, chickens, and catfish; genotoxic effects have been demonstrated in other nontarget organisms (Cox 1995 a,b). Earthworms have been shown to be severely damaged by the glyphosate herbiocide at 2.5–10 l/ha. (Rebanova et al. 1996). For example, Allolobophora caliginosa, the most common earthworm in European, North American, and New Zealand fields is damaged by this herbiocide (Mohamed et al. 1995; Springett and Gray 1992). In addition, aquatic organisms, including fish, can sometimes be severely damaged (Henry et al. 1994; WHO 1994). The prevalence of the nematode Steinernema feltiae, a useful biological control organism, is reduced by 19–30% by use of this herbiocide (Forschler et al. 1990).

Health Risks

The unknown health risks associated with the use of herbicides (as well as most xenobiotics) involve the effects of low-level chronic exposures (Wilkinson 1990). Although most research has addressed cancer risk, much less research has been focused on neurological, immunological, developmental, and reproductive effects (Krimsky and Wrubel 1996). Much of this problem reflects the dearth of methodologies and diagnostic tests at the disposal of scientists necessary to evaluate the risks caused by exposure to many chemicals, including herbicides, properly.

Although industry often stresses the desirable characteristics of their HRCs, environmental and alternative agriculture groups, as well as some scientists, disagree, with the contention that these products are safe. For example, research has shown that the application of glyphosate can increase the level of plant estrogens in the bean Vicia faba (Sandermann and Wellman 1988). Feeding experiments have shown that cows fed transgenic glyphosate-resistant soybeans had a statistically significant difference in daily milk fat production compared with other test groups (Hammond et al. 1996).

Increased Costs Associated with Use of HRCs

Because the herbicides for which HRCs are being designed are almost all under patent, they will be more expensive than many of the herbicides they are intended to replace (Fig. 1). In addition, although analysts project that, for example, switching to bromoxynil for broadleaf weed control in cotton could result in savings of $37 million each year from reductions in herbicide purchases of 40% to 50%, few economic product evaluations that demonstrate cost savings with the use of HRCs have been published (Krimsky and Wrubel 1996). Furthermore, recent problems with use of glyphosate-resistant cotton in the Mississippi Delta region (crop losses resulting in up to $500 thousand of this year's cotton crop) suggest this technology needs to be perfected further before some farmers will reap economic benefits (Fox 1997).

Some scientists suggest that use of HRCs will cause a shift to the use of fewer broad-spectrum herbicides, which will reduce the amount of sprays and the amount of herbicide used per application (Hayenga et al. 1992), others contend that the overall use of HRCs will actually increase herbicide use and thereby increase costs associated with their application (Goldburg et al. 1990; Rissler and Mellon 1993; Paolletti and Pimentel 1995; Paolletti and Pimentel 1996).

Bacillus thuringiensis (BT) for Insect Control

More than 40 BT crystal protein genes have been sequenced and 14 distinct genes identified and classified into 6 major groups based on amino acids and insecticidal activity (Krimsky and Wrubel 1996). Many crop plants have been engineered with the BT δ-endotoxin, including alfalfa, corn, cotton, potatoes, rice, tomatoes, and tobacco (Table 3). The amount of toxic protein expressed inside the modified plant is 0.01–0.02% of the total soluble proteins (Strizhov et al. 1996).

Potential Economic and Environmental Benefits

Corn

Supporters of BT usage cite current trials demonstrating a high level of efficacy in controlling corn borer damages on plants. Corn engineered with BT δ-endotoxin has the potential to recover 5–15% of corn borer damage in 70 million acres in the United States with a projected benefit of $50 million annually (Steffy 1995). However, without careful management tactics based on university agriculture extension and technical expertise, growers and seed suppliers could see unforeseen environmental risks.
Cotton

Cotton was the first crop plant engineered with the BT δ-endotoxin released into the market. It has been estimated that caterpillar pests, including the cotton bollworm and budworm, cost U.S. farmers about $171 million/year as measured in yield losses and insecticide costs (Head 1991). Benedict et al. (1992) predicted that the widespread

TABLE 3. Transgenic insect-resistant crops containing BT endotoxins. Approved field tests in United States from 1987 to July 1995

<table>
<thead>
<tr>
<th>Crop</th>
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<tbody>
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Source: Adapted from Krimsky and Wrubel 1996 and Gene Exchange, 1996.
use of BT-cotton could reduce insecticide use and thereby decrease costs by as much as 50 to 90%, which would save farmers $86 to $186 million/year, respectively.

Potatoes

Genetically engineered Russet Burbank potatoes with Bacillus thuringiensis tenebrionis (the δ-endotoxin is represented inside the engineered potatoes at 0.05–0.1% CryIII A as a percentage of total protein) have been shown to be successful (Perlak et al. 1993). This formulation is also suggested as a base to develop an effective and sustainable IPM program for potatoes.

Eggplants

The δ-endotoxin Cry3b-engineered eggplants have demonstrated consistent effects against potato beetles (Jannaccone et al. 1997). However, resistance is one harrowing prospect, and proper resistance management has to be considered.

Potential Environmental Risks

Insects that develop resistance to transgenic crop varieties are one of the possible risks associated with the use of BT δ-endotoxin in genetically engineered crop varieties. Resistance to BT has already been demonstrated in the cotton budworm and bollworm (Tabashnik 1992; Bartlett 1995). If BT-engineered plants become resistant, a key insecticide that has been utilized successfully in IPM programs, could be lost (Paoletti and Pimentel 1995). Therefore, proper resistance-management strategies with the use of this new technology are imperative. Another potential risk is that the BT δ-endotoxin could be harmful to nontarget organisms (Goldburg and Tjaden 1990; Jepson et al. 1994). For example, it is not clear what potential effect BT δ-endotoxin residues that are incorporated into soils will have against an array of nontarget useful invertebrates living in the rural landscape (Jepson et al. 1994; Paoletti and Pimentel 1995).

Recycling of Toxic Wastes and Improved Waste Management

Advances in technology have resulted in the availability of a variety of chemicals, many of which have increased ecosystem pollution. Currently, in the United States, some 70,000 different chemicals are released into the environment through soil, water, and air (Newton and Dillingham 1994); an estimated 100,000 chemicals are used worldwide (Nash 1993). Cleanup of hazardous wastes by conventional technologies is projected to cost between $400 and $750 billion in the United States alone on the basis of estimates obtained from a variety of federal and private sources (Salt et al. 1995; USGS 1995). Various strategies that are utilizing genetic engineering and biotechnological methods to deal more efficiently with waste removal and management include bioremediation, phytoremediation, and the production of biodegradable plastics.
Bioremediation

Biotechnology and genetic engineering may help reduce environmental pollution through bioremediation, which is the application of biological treatments using microbes to degrade chemical materials at polluted sites effectively. Because bioremediation provides continuous cleanup of contaminated sites, such as pesticide residues in agricultural ecosystems, it has significant advantages over other techniques. Furthermore, a marked degree of self-regulation is present in such systems because the added microbes survive by consuming and degrading chemicals but die off when the nutrient source is reduced or eliminated (Pimentel et al. 1997).

Investigations into genetically modified bacteria for bioremediation have produced a strain of *Pseudomonas cepacia* that degrades a wide spectrum of chemical pollutants, including vinyl chloride, dichloroethylene, phenol, toluene, xylenes, and creosol (EPA 1991). Most importantly, this bacterium produces an enzyme that is capable of degrading dichloroethylene, a persistent industrial degreaser. Bioremediation techniques are growing in importance and diversity as new approaches are developed to use both wild and genetically engineered biota for chemical pollution abatement.

Phytoremediation

Phytoremediation, or the use of specially selected and engineered metal-accumulating plants for environmental cleanup, is an emerging technology that may serve as a cost-effective approach to treating soils and groundwater contaminated with toxic metals (Salt et al. 1995). Currently, cleanup of sites in the United States contaminated with heavy metals and organic mixtures can alone cost $42.5 billion. Phytoextraction, or the use of metal accumulating in plants to remove toxic metals from soils, could be utilized to clean up sandy loam soils to a depth of 50 cm, which would cost $60,000–$100,000 compared with at least $400,000 for excavation and storage alone using traditional soil removal methods (Salt et al. 1995). Rhizofiltration, or the use of plant roots to remove toxic metals from polluted waters, may offer an advantage in water treatment because of the ability of plants to remove 60% of their dry weight as toxic metals, thus markedly reducing the generation and disposal costs of hazardous radioactive residue. Rhizofiltration could also be a cost-competitive technology in the treatment of groundwater containing low concentrations of toxic metals.

Genes encoding the cadmium-binding protein, metallothionein, have been recently shown to be expressed in plants. A research group at Peking University has engineered a human gene encoding metallothionein (a protein that binds heavy metals) into tobacco. The genetically engineered plants have survived exposure to cadmium concentrations that were 25 times greater than the dose that killed control plants. More importantly, these genetically engineered plants have also been shown to absorb cadmium from the soil. Researchers are also now engineering the gene into weeds in the hope of using the transgenic weeds to reduce heavy metal contamination on farmland (Chen and Gu 1993).

Biodegradable Plastics

Another area of waste management biotechnology and genetic engineering could play a role is in the production of biodegradable plastics. Currently, plastics account for 20% by volume of all municipal solid wastes (Stein 1992). Estimates of the current global market for biodegradable plastics range up to 1.3 billion kg per year (Lindsay 1992). However, until recently, the cost of these biodegradable plastics, such as polyhydroxyalkanoates (PHAs), polymers made entirely by bacterial fermentation, has been one of the major limiting factors in their use (Poirier et al. 1992, 1995). Producing PHAs in plants would significantly reduce the expense of manufacture compared with fermentation and make these biopolymers competitive with petroleum-based plastics for low-cost uses (Poirier et al. 1995; Nawrath and Somerville 1995).

Recently, efforts to produce PHAs in plants have been successful. Bacterial genes that are necessary to synthesize polyhydroxybutyrate (PHB), a type of PHA, were transferred to *Arabidopsis thaliana* plants. The genetically engineered plants accumulated up to 14% dry weight of PHB without deleterious effects on plant growth or fertility and with a level of polymer yield that is considered commercially practical (Nawrath, Poirier, and Somerville 1994). Several companies are now pursuing development of PHA-producing genetically engineered oilseed rape (canola) crops (Poirier et al. 1995; Wragg 1995).

Environmental Risks

In initial prerelease testing, the interactions of such new genetically engineered organisms with non-target organisms in the soil communities and contaminated landscapes must be carefully monitored to avoid potentially deleterious side effects (Paolletti and Pimentel 1996). Also, it will be important to monitor the safe environmental disposal of plants that accumulate toxic materials.

NOVEL FOOD PRODUCTS

The objective of biotechnology and genetic engineering is to improve the food supply by increasing crop and livestock productivity, enhancing nutrient composition and availability, and improving food characteristics such as size, taste, and texture. The following are examples of the types of applications that have been achieved or are under way.

Increased Crop and Livestock Productivity

In the past, scientific breeders of plants and animals have utilized the rich genetic resources of cultivars and land races in crop improvement programs. It has been estimated that at least half of the increase in agricultural productivity realized this century
may be directly attributable to "artificial selection, recombination, and intraspecific gene transfer procedures" (Woodruff and Gall 1992). Use of biotechnology and genetic engineering may result in greater productivity gains through high-yield crop varieties, improved pest and disease control, the production of herbicide-resistant crops, enhanced nutrient availability, and tolerance to a variety of environmental factors (Mannion 1995).

Biotechnology is also being used as a way to increase livestock productivity by enhancing milk and meat production. This is achieved by isolating the gene for the protein hormone (e.g., somatotropin) made in the anterior pituitary gland of animals and inserting it into bacterial cells, which results in increased production of the hormone. Applications of this technology include the injection of recombinant bovine somatotropin (rBST) into dairy cows to increase milk production and injection of recombinant growth hormone (rGTH) into growing pigs to increase carcass leanness and decrease fattiness (Etherton 1994). Some authors have speculated that decreasing the quantities of feed consumed per unit of output may benefit the environment by decreasing environmental pollution through reducing the quantity of feed provided; reducing the quantity of fertilizer and other inputs associated with growing, processing, and storing animal feed; and reducing animal waste products (Etherton 1994; van Weerden and Verstegen 1989).

Biotechnology may also play a role in improving crop plants that, in turn, enhance secondary productivity in livestock (Mannion 1995). Researchers at the Commonwealth Scientific and Industrial Research Organization's division of plant industry in Canberra have found a way to insert a sunflower gene into the subterranean clover, a major constituent of Australian sheep pastures. The new clover, with genes from sunflower that code for a protein in sulfur amino acids, provides sheep with a sulfur-rich diet that is necessary for wool production. Creating such a transgenic clover resulted in about a hundredfold increase in the sulfur-rich protein. However, it has been estimated that (i.e., an increase in wool production by 5-10%), the level of sulfur-rich protein needs to be boosted another tenfold to have a substantial impact on wool production. The group is testing gene promoters that could achieve this. Producing the same amount of wool from fewer sheep could reduce soil erosion and other environmental pollution produced by these animals (Thwaites 1993).

Developments in biotechnology and genetic engineering may also be able to improve ruminant nutrition by modifying the microbes that are involved in ruminal fermentation. The objective will be to find suitable foreign bacterial genes that can be inserted into ruminal bacterial organisms (Wallace 1994). Techniques of genetic engineering are also playing an important role in increasing animal productivity by improving and developing vaccines and pharmaceuticals (e.g., fertility hormones). Hybridoma technology, which results in the generation of monoclonal antibodies by cell fusion procedures, will be increasingly useful in diagnosing specific diseases as well as in disease prevention and treatment (Woodruff and Gall 1992). The broad range of potential vaccines for control of various diseases is especially promising because of their low environmental risks and excellent socioeconomic benefits (Paolelli and Pimentel 1996).

Enhanced Nutrient Composition and Availability

Enhanced Nutrient Composition

Another application of biotechnology in agriculture is intended to improve the food supply by enhancing the nutritional composition of foods. In 1992, Monsanto was able to produce a genetically engineered potato successfully with an increased starch content. A lower starch content reduces oil absorption during frying and thereby lowers the cost of frying certain food products (e.g., French fries, potato chips) and reduces oil content in the finished product (Zimmen and Voichick 1994). Genetically engineered strains of oilseed rape (canola) are undergoing development at Calgene, where applications include high-oleic-oil-content margarine and edible canola oil with reduced saturated fat content (Krimsky and Wnubel 1996).

Through biotechnology, scientists also hope to create foods that protect against cancer, heart disease, osteoporosis, and other life-threatening illnesses. For example, the National Cancer Institute (NCI) is currently working on increasing the amount of phytochemicals, which are linked to cancer prevention, in foods such as garlic, parsley, and citrus fruits. Government, university, and industry scientists are also developing cereal grains with increased amounts of both soluble and insoluble fiber to lower cholesterol and fight digestive cancers, respectively; milk with improved calcium bioavailability to help protect against osteoporosis; and vegetables with boosted levels of antioxidants (e.g., super carrots with five times the amount of β-carotene) to help reduce the risk of cancer (Rohlfing 1991).

Enhanced Nutrient Availability

Biotechnology and genetic engineering can also be employed to enhance nutrient availability in agricultural systems. Genetic engineering has been applied to the problem of nitrogen fixation with a specific focus on the genetic makeup of organisms that fix nitrogen from the atmosphere and the genetic basis for the relationship between leguminous species (e.g., peas, beans, alfalfa, clover, peanuts) and the nitrogen-fixing bacteria that occupy their nodules (Mannion 1995). Scientists in China have recently developed recombinant strains of nitrogen-fixing bacteria that have a higher nitrogen fixation efficiency than traditional bacteria. These recombinant strains of bacteria have been spread over more than a million hectares of rice and soybean fields, and preliminary results show crop yield increases of 5-10% (Chen and Gu 1993).

In addition, a mechanism of biological nitrogen-fixation similar to that of natural legumes eventually may be genetically engineered into plants such as wheat and corn. If this is achieved, the need for commercial nitrate fertilizers could be significantly reduced (Mannion 1995). However, because the molecular mechanisms required for
symbiotic nitrogen fixation are complex (involving at least 17 genes), achieving this will require an investment in research over several decades (Woodruff and Gall 1992).

Other Improved Food Characteristics

Other applications of biotechnology to improve the food supply include the improvement of certain food characteristics such as size, ripeness, acidity or sweetness, taste, and texture. Genetic modifications have enabled the production of fruit that may have better taste and an enhanced shelf life through delayed pectin degradation (Bennet et al. 1989) or altered responses to the plant hormone ethylene (Bleecker 1989). Among the first of such novel products on the market was Calgene's slow-ripening Flavr Savr® tomato, which was approved for sale by the Food and Drug Administration in May 1994. This tomato has been transfected with an "antisense" gene responsible for the enzyme polygalacturonase, which solubilizes pectin (Holden 1989). Because pectin degradation increases fruit ripening and decreases shelf life, preventing translation of the message (by having the antisense message present) for polygalacturonase should retard fruit ripening and increase purchase and postpurchase shelf life (AMA 1991). DNA Plant Technology (DNAP) corporation's Endless Summer® tomato, which like Calgene's Flavr Savr has an antibiotic-resistance marker gene encoded into it, also incorporates a gene-splicing technique to retard ripening (Cummins 1995).

Risks

Environmental Risks

The production of plants and animals to suit specific environments could lead to the transformation of more land presently occupied by natural ecosystems into agricultural land. The ecosystems of the tropics on the land not suited for agriculture of any kind are particularly vulnerable. Thus, the removal of yet more natural ecosystems would further deplete biodiversity. Genetic engineering may also favor monocultures that will threaten the global centers of ordered biodiversity (Hopkins et al. 1991; Rissler and Mellin 1993; Third World Network 1995).

Health Risks

One potential health risk is related to the use of genetically engineered animal hormones. One can illustrate using the case of rBST. The Food and Drug Administration has ruled that the presence of rBST in milk is safe for children and adults (FDA 1995). Even so, there have been questions regarding the impact of this technology on animal and human health (Broom 1995). Use of rBST in dairy cows increases the chances of bacterial infections and mastitis and also reduces the reproductive cycle in treated dairy cows (GAO 1992; Burton et al. 1994; Broom 1995). Milestone et al. (1994) report that increased infections in cattle will require treatment with antibiotics. Although not all antibiotics appear in milk, some do. Thus, if more antibiotics are used, an indirect risk to humans may arise because some residues may remain in the milk (GAO 1992).

A second potential human health concern is the risk of introducing allergens into the food supply. A recent study by Nordlee and colleagues demonstrated the transfer of a major food allergen from Brazil nuts to transgenic soybeans during the development of a genetically engineered crop variety (Nordlee et al. 1996). Furthermore, although only a dozen foods may produce allergic reactions—mainly protein foods—biotechnology allows for nontraditional food proteins (e.g., moths, insects) to be present for which no knowledge currently exists regarding their allergenic or nonallergenic qualities (Nordlee et al. 1996).

A third potential human risk relates to the increasing prevalence of antibiotic-resistant and disease-causing bacteria. Because antibiotic-resistant genes are the most commonly used type of selectable marker in genetic engineering and are rarely deleted from the resulting organism, incorporation of antibiotic-resistant markers into the genetic material of human pathogens could pose risks by increasing the prevalence of antibiotic-resistant and disease-causing bacteria. In 1989, dozens of people died and thousands others were crippled after consuming a batch of synthetic L-tryptophan produced using genetically-engineered bacteria. Although the exact cause of illness will never be known, it has been reported that a specific impurity stemming from the bacterial strain may be cause of the syndrome (Raphals 1990).

A fourth health concern is that genetically engineered crops may be able to transfer their foreign gene(s) to other unrelated microorganisms. Genetically engineered oilseed rape (canola), black mustard, thorn-apple, and sweet peas all contain an antibiotic-resistance gene and were grown together with the fungus Aspergillus niger, or their leaves were added to the soil. The fungus was shown to have incorporated the antibiotic-resistance gene in all coculture experiments. (Hoffman et al. 1994).

Other health risks created through the use of biotechnology and genetic engineering include the ability of genetically engineered organisms to survive and harm nontarget organisms, the creation of new toxic organisms, or both (Goldburg and Tjaden 1990; Jepson et al. 1994). The risk of a new host being infected by a virus or recombining to form a more deadly, virulent virus must be investigated further (Green and Allison 1994; Tepfer et al. 1994). For example, the risk of recombination between the engineered vaccine virus and other orthopox viruses endemic in wildlife, such as the cowpox virus, still needs to be investigated accurately (Boulanger 1995).

Social and Economic Impact

Proponents often cite biotechnology and genetic engineering as the way to help solve the world's food problems (i.e., improve agriculture in developing countries). However, some critics who are skeptical about ability of biotechnology and genetic
engineering to increase food production by about 1% in crop yield on the basis of the anticipated benefits of biotechnology during the next two decades (Duvick 1989; Brown et al. 1990). In addition, no increase in crop yields is projected for Africa because no major advances in biotechnology are expected to be applied in Africa in the near future (Pimentel et al. 1992a).

Some persons further question why, after 20 years of research, biotechnologists have not produced a single high-yielding variety of wheat, rice, or corn. The answer, according to plant scientists, is that plant breeders using traditional techniques may have largely exploited the genetic potential for increasing the share of photosynthate that goes into the seed (Brown 1997). Others feel that the present channeling of funds to expensive biotechnology projects diverts scarce resources from other research that could focus on more practical solutions to pressing social problems such as hunger and food insecurity (Third World Network 1995).

Some authors (Krimsky and Wruble 1996) have also observed that many of the crops being engineered for herbicide resistance belong to the group of key crops in Western agriculture. This circumstance may reflect the dominance of the majority of the biotechnology industry by transnational companies (TNC) in the developed world whose business it is to generate profits (Mannion 1995). If sustaining the Third World is the target of genetically engineered crops, other vegetables and crops have to be considered. Also, helping these countries bypass expensive, high-input crop production and move their traditional agriculture toward low-input sustainable practices is desirable as well (Odum 1989).

**TRANSGENIC ANIMALS**

**Benefits**

Among the benefits of producing genetically engineered or transgenic animals are the ability to manufacture more cost-effective drugs (including vaccines), new animal models to study human disease, human tissue and organ harvesting, and improvements in the food supply (e.g., modifying the shape, size, or nutritional quality of animals). In the early 1980s, the first successful experiments creating transgenic vertebrates were reported (Krimsky and Wruble 1996). Palmiter et al. (1982) created a transgenic mouse by transferring a growth hormone into the embryo of the mouse. In 1988, a patent was awarded for a mouse that was genetically engineered with human genes designed to be tumorigenic. This mouse, commonly referred to in the scientific literature as the "oncomouse," (oncology is the study of tumors), prompted the first patent issued for a transgenic animal (OTA 1989).

Transgenesis, or the transfer of genes across species lines, opened the way for animals to be used as an alternative to tissue-culture productions of human protein (Krimsky and Wruble 1996). In 1987, a transgenic mouse was created that demonstrated the viability of tissue-specific expression of foreign proteins (Gordon et al. 1987). As reported by Krimsky and Wruble (1996, p. 192), "The mouse was genetically engineered to make the clot-dissolving factor tissue plasminogen activator (TPA), which is viewed as a highly promising drug for the treatment of coronary heart disease and a strong competitor of the widely acclaimed streptokinase."

Krimsky and Wruble (1996) also note, "Finnish researchers have developed a genetically-modified cow that purportedly can produce milk containing large amounts of erythropoietin (red cell growth factor) used to treat anemia. If successful, this method will replace the costlier cell culture techniques. Other more remote applications of transgenic animals include human blood and organ production." (Krimsky and Wruble 1996, p. 195).

Transgenic animals under development include swine with the human growth hormone gene, genetically engineered livestock designed to tolerate extreme climatic conditions, transgenic sheep that grow faster than normal sheep, engineered sheep that secrete insect repellent and produce moth-proof wool, and genetically engineered sheep and cows that produce milk consumable by lactose-intolerant individuals (Krimsky and Wruble 1996). Many different species of fish are being genetically engineered to increase fish size and growth rate or improve survival in new environments. Genetic engineers have turned much of the attention toward finfish and shellfish (Warmbrodt 1993).

Many species of transgenic fish have been grown in the laboratory. Fast-growing Pacific salmon have been engineered by various groups of researchers worldwide. Scientists attached a switch to a growth hormone gene from coho salmon and injected the transgene into chinook salmon eggs. On average, the transgenic salmon grew to be elevenfold heavier than their age-mates (Devlin 1994). Fast-growing fish have also been produced outside the laboratory. In 1991, transgenic carp were tested in a high-acidity pond at Auburn University. These fish were fitted with a growth hormone gene from rainbow trout that enabled them to grow 40% faster than normal (Fishetti 1991). Researchers have also identified a protein in winter flounder, which has recently been transferred into Atlantic salmon, that prevents fish blood from freezing. Transgenic salmon with this trait could potentially be raised in sea pens farther north, where the species could not otherwise live (Fletcher 1992).

**Risks**

**Environmental**

Very real environmental risks may be associated with transgenic animals—particularly with certain applications, such as transgenic fish (Goldburg 1995; Regal 1994). For example, transgenic fish have the potential to disturb ecosystems seriously by gaining a competitive advantage in the wild ecosystem. A fast-growing transgenic fish could assume a higher than usual position in the food chain because of its greater size and ability to compete for food, which could harm native species, or a freeze-tolerant transgenic fish raised in the north could escape into a geographic area from which it was previously excluded, and cause competition that would harm native species.
(Kapuscinski and Hallerman 1995). Fertile transgenic fish could also successfully invade ecosystems, thus exacerbating the present problem with exotic invaders in aquatic ecosystems (Carlton and Geller 1993).

Health

Using transgenic animals to harvest blood, tissues, or organs may create certain health risks. For example, take the case of deriving human hemoglobin from transgenic pigs. Human hemoglobin must be separated from that of the animal to ensure the purity of the product. Also, how humans will respond to such animal-derived human hemoglobin is still untested (Krimsky and Wrubel 1996).

Social and Ethical

Finally various social and ethical risks are associated with the production and use of transgenic animals. Certain animal rights groups (e.g., The Humane Society) question whether it is morally or ethically correct to turn animals such as mice, pigs, and sheep—which unlike plants and bacteria are sentient beings—into biomachines for the manufacture of proteins and other biological materials (Fox 1992). Some groups may also find it unethical to introduce human genes into livestock and plants. This application of genetic engineering could raise ethical concerns and seriously undermine the public's perceptions of biotechnology (Buttel 1988; Reiss and Straughan 1997). Religious groups may also have certain conflicts as to whether this new technology is compatible with their traditional norms. There may also be a conflict of interest within the value and belief systems of those groups for whom it is abhorrent to manipulate, control, experiment with, or consume animals of any type (Krimsky and Wrubel 1996).

GENERAL RISKS OF RELEASING GENETICALLY ENGINEERED ORGANISMS INTO THE ENVIRONMENT

Single-Gene Changes and Pathogenicity

Most single-gene changes are probably not likely to affect the pathogenicity and virulence of an organism in nature adversely (NAS 1987). However, some gene changes may have detrimental consequences. Certain genetic alterations in animal and plant pathogens, for example, have led to enhanced virulence and increased resistance to pesticides and antibiotics (Alexander 1985). For instance, some oat rust microbes, initially nonpathogenic for a particular oat variety, became serious pest genotypes after a single gene change allowed the rust to overcome resistance in the oat genotype (Wellings and McIntosh 1990).

An important fungal disease of rice, rice blast, has been demonstrated to have genotypes with single-gene changes that cause the fungal organism to be potentially pathogenic to rice cultivars (Smith and Leong 1994). A similar phenomenon of single-gene changes resulting in pathogenicity has been documented with a related fungal pathogen that infects weeping love grass (Heath et al. 1990). This phenomenon has led plant pathologists to develop the "gene-for-gene" principle of parasite-host relationships in which a single mutation in a parasite overcomes single-gene resistance in the host (Person 1959). Furthermore, numerous instances have been documented in which insects, through a single-gene change, have overcome resistance in plant hosts or have evolved resistance to insecticides (Roush and McKenzie 1987). More than 500 species of arthropods have developed resistance to pesticides (Georgiou 1990).

Threats from Modified Native Species

Lindow (1983) has reported that there is little or no danger from the ice-minus strain of Pseudomonas syringae (Ps) because Ps is a native U.S. species that produces related phenotypes in nature. Other investigators have demonstrated that there are different genotypes of Ps, and some of these genotypes have genes for pathogenicity (Lindgren et al. 1988). Because some native species have the ability to alter their interactions within an ecosystem, the genetic modification and release of native species into the natural ecosystem may not always be safe. For example, from 60 to 80% of the major insect pests of U.S. and European crops, respectively, were once harmless native species in the United States and Europe (Pimentel 1993b). Many of the insects moved from benign feeding on natural vegetation to destructive feeding on introduced crops. For instance, the Colorado potato beetle moved from feeding on wild sandbar to feeding on the potato that was introduced from Peru and Bolivia (Elton 1958). This insect has become a serious pest of the potato in the United States and Europe.

Intentional Introduction of Crop Plants and Animals

Some proponents of biotechnology suggest that the intentional introduction of foreign plants and animals into the United States is a good model for predicting potential problems arising from biotechnology (NAS 1987). If so, there is reason for concern because several serious problems have resulted from the intentional introduction of what were believed to have been beneficial crops and animals. Genetic similarities between many of the crops and weeds are evident from the fact that 11 of the 18 most serious weeds of the world are crops in other regions of the world (Colwell et al. 1985). Of the several thousand crops that were intentionally introduced into the United States, 128 species of agricultural and ornamental plants have become serious pest weeds (Pimentel et al. 1989). Some of these introduced plant species, like Johnson grass, are among the most serious weed species in the United States—
especially in the southeastern United States. Johnson grass was introduced as a forage for livestock before it escaped and became a weed pest.

This pattern of native species and introduced plants species in the United States is not unique. For example, Florida has only 2525 indigenous plant species, but approximately 25,000 plant species have been introduced and are under cultivation there (Table 4) (Frank and McCoy 1995). An additional 925 species of exotic plants are established in nature in Florida, and several of these are currently displacing native plant species (Table 4). One exotic pest that is displacing native plant species is the melaleuca (Melaleuca quinquenervia) tree introduced from Australia. This clearly illustrates the threat to our natural ecosystem when so-called beneficial organisms are introduced and released into nature. The picture in Florida for insects is quite different than for plants (Table 4).

The great majority of insects species (11,512) are native, with nearly 1000 immigrant species. A relatively small number (42) of insect species are established in nature. One of these species that has established itself and is a serious pest in nature is the imported fire ant (Frank and McCoy 1995). Furthermore, 9 out of 20 introduced domestic animal species in the United States have displaced or destroyed native species (Pimentel et al. 1989). These introduced domestic animals, including donkeys, horses, and goats, have become serious ecological pests. A total of 10 other introduced animals, including mammals (e.g., mongoose and wild boars) and birds (e.g., English sparrow and mynah), have become pests (Pimentel et al. 1989).

Furthermore, at least 70 species of fish have been introduced and have become established in U.S. aquatic ecosystems (Courtenay and Moyle 1992). These 70 species represent about 10% of all U.S. fish species. A total of 5 introduced fish species have become pests, displacing and reducing the number of native species and, in other cases, altering the habitat and making it uninhabitable for fish and other species (Courtenay and Moyle 1992). In addition to these intentionally introduced fish, there is concern about the introduction of transgenic fish and the potential ecological effects of these engineered fish in aquatic ecosystems in the United States (Kapuscinski and Hallerman 1991). This overall history suggests that the introduction of many types of foreign organisms in the ecosystem may have major negative impacts on many of the 500,000 beneficial plants and animals in the United States (Pimentel et al. 1992).

Are Ecological Niches Filled?

An estimated 1500 exotic insect species have been introduced and are established in the United States, and a few of these (17%) have become pests or have a negative impact on native species (Sailer 1983). This observation indicates that few of the niches in natural ecosystems are filled (Colwell et al. 1985; Herbold and Moyle 1986). There is ample opportunity, therefore, for many species to become established in the United States. Thus, although the argument that engineered organisms will not become established owing to competition with native species may apply in a few cases, most often this is not a valid argument (Pimentel et al. 1989).

USES OF BIOTECHNOLOGY AND GENETIC ENGINEERING FOR A SUSTAINABLE AGRICULTURAL SYSTEM

Acceptable and potentially sustainable options for agriculture that could be derived from biotechnology and genetic engineering have been put forward by several authors (Paolotti and Pimentel 1995, 1996). Some of the desirable areas of development for such technologies that have the potential to benefit agricultural sustainability, the integrity of the natural environment, and the health and safety of society are discussed in the following paragraphs.

Enhancing Crop Resistance to Pests

Approximately 500,000 kg of pesticides are applied each year in U.S. agriculture, and many nontarget species beneficial to the environment are negatively affected. Genetic engineering targeted for pest control could diminish the need for pesticides (Pimentel et al. 1992).

Resistance factors and toxins that exist in nature can be used for insect pest and plant pathogen control (Pimentel 1988). For example, more than 2000 plant species are known to possess some insecticidal activity (Crosby 1966), and approximately 700 natural substances in bacteria, fungi, and actinomycetes have fungicidal activity (Marrone et al. 1988). Traits for resistance to different insect pests and diseases already exist in many cultivated crops, including corn, wheat, barley, soybeans, beans, apples, grapes, pears, tobacco, tomatoes, and potatoes (Russell 1978; Smith 1989).

Although some resistance characteristics have been reduced or eliminated in commercial crops, they still can be found in related wild varieties, which provide an enormous gene pool for the development of host-plant resistance (Boulter et al. 1990). For example a wild relative of tobacco that produces a single acetylated derivative of nicotine is reported to be 1000 times more toxic to the tobacco hornworm than cultivated tobacco (Jones et al. 1987).

Transferring this toxic gene to nonfood crops, such as ornamental shrubs and trees, may protect them from certain insect pests. In addition, thionins, proteases, lectins, and chitin-binding proteins that are often present in plants, especially in the seeds, help control some pathogens and pest insects in wild plants (Pimentel 1988; Garcia-Olmedo et al. 1992; Boulter et al. 1990; Czapla and Lang 1990, Raikhel et al. 1993). For example, it has been shown that a cowpea protease inhibitor found in the cowpea Vigna spp. can now be engineered into tobacco (Gatehouse et al. 1993). Laboratory trials also indicate that the cowpea protease inhibitor provides protection against the cotton bollworm (Heliotis virescens), which is a major pest of tobacco, cotton, and maize (Minnion 1995).
Development of Perennial Crops

At present, the major cereal crops of the world are annuals. The conversion of annual grains to perennial grains by genetic engineering will reduce tillage and erosion and conserve water and nutrients (Jackson 1991). Such crops will decrease labor costs, improve labor allocation, and, overall, improve the sustainability of agriculture. Energy efficiency in cultivation of perennial cereal crops will be greatly superior to that of annual crops (Jackson 1991).

Improved Botanical Pesticides

Only limited quantities of botanical pesticides, such as pyrethrums, are now used in developed countries in place of some synthetic pesticides. However, in some developing countries, including China and India, botanical pesticides such as neem are effectively used (NAS 1992; Vietmeyer 1992). Increasing the effectiveness of neem and other available botanical pesticides by genetic engineering would be an asset to farmers because these substances are relatively effective and safe.

Bioindication Needs for Sustainable Use of Genetically Engineered Plants

Bioindication is a strategy that adopts and assesses biological units, species, assemblages of species, and ecosystem models to determine the impact of a selected contaminant such as pesticide residues or fertilizers on the environment (Paolletti and Bressan 1996; Paolletti 1997). This strategy is aimed at using biological nontarget organisms, both in microcosm-modeled and in field arenas, to assess the environmental problems created by adopting certain new management techniques in agroecosystems, including genetically engineered organisms. As observed by several authors (Jepson et al. 1994; Paolletti and Pimentel 1995; Paolletti and Pimentel 1996), little work has been dedicated to assessing the true environmental impacts of genetically engineered crop plants (Rissler and Mellson 1995). For example, there are no data on pollinators of engineered plants modified with the BT δ-endotoxin. It would be rather useful to work with the nontarget species linked to the rural landscapes in which the genetically modified crops are expected to be introduced.

PUBLIC PERCEPTIONS OF BIOTECHNOLOGY

Current public opinion polls show that consumers find some applications of biotechnology and genetic engineering more acceptable than others (Hoban and Kendall 1992; Martin and Tait 1992). For example, in a national random telephone survey conducted in the United States by Hoban and Kendall (1992), 66% of respondents considered plant-to-plant gene transfers acceptable, 25% found animal-to-plant gene exchanges acceptable, 40% found animal-to-animal gene transfers acceptable, and only 10% approved of human-to-animal gene transfers.

A survey of public attitudes toward biotechnology in the United Kingdom revealed that a large percentage of respondents would accept genetically manipulated foods if under the condition they were confident about testing and that the food product(s) look and taste the same or better. One-half of respondents felt it would be a good thing to use genetic manipulations to solve the food problems in the Third World, whereas relatively few people felt it would be a good thing to use genetic manipulation to provide or improve the food supply in the Western world. A majority of respondents (79%) also felt that it would be a bad thing to use genetic manipulation for products they did not feel were needed (Martin and Tait 1992). Consumer surveys in the United States also suggest that the public is skeptical and cautious with regard to certain applications of biotechnology in agriculture and food production (Hoban and Kendall 1992; Wyse and Krivi 1987). Consumer apprehensions center around biotechnology’s perceived unpredictability, risks to the environment, and moral and social questions (Bruhn 1992).

In Europe, public attitudes toward genetically engineered foods appear less favorable than in the United States (Krimsky and Wurzel 1996). Recently, the European Commission has approved mandatory labeling of all genetically modified organisms (GMOs). The European community states that the intent of the label is to serve as a source of information for consumers, not as a warning (Institute for Agriculture and Trade Policy 1997). Results from consumer surveys in the United States, Canada, and the United Kingdom also indicate that most consumers are in favor of labeling genetically engineered foods (Feder 1997; Slusher 1991; Optima Consultants 1994; Martin and Tait 1992).

USE OF BIOTECHNOLOGY AS A WAY TO PRESERVE BIODIVERSITY

Benefits

Proponents of biotechnology claim that use of biotechnology and its subdiscipline of genetic engineering is needed to renew the momentum of plant and animal genetics and is one of the factors that has contributed to food production gains achieved thus far (Avery 1993). Advocates also claim that biotechnology has the potential to enhance species preservation, increase the value of biodiversity, and promote ecosystem conservation through decreased environmental degradation.

Enhance Species Preservation

The International Board for Plant Genetics (IBPGR) as well as many others has taken up the job of collecting critically valuable germ plasm. The IBPGR gene banks now have more than a half a million plant "accessions" representing thousands of varieties...
and hundreds of different species. Biotechnology has encouraged the collection of genes through germ plasm secondary to its being viewed as a valuable and prosperous activity. Utilizing biotechnology for collecting germ plasm may help ensure the world's biodiversity is maintained by fostering preservation of species that are in danger of becoming displaced by new varieties (IBPGR 1992).

Increase the Value of Biodiversity

Biotechnology may increase the value that is placed on biodiversity through increased returns on investments in research and development of biotechnologies that may generate animal and crop breeds of potential value. The present economic benefits of biotechnology products are significant and are conservatively estimated to be between $2–3 billion/yr in the United States alone. Worldwide, current benefits are about $6.2 billion/yr. Nearly half of the current economic benefits relate to agriculture with significant benefits to the pharmaceutical industry (Kathuri et al. 1993). For example, biotechnology, in the form of bioassays, has reduced the time and cost of screening for pharmaceutical and other uses and has thus increased the value of the underlying genetic resources. For this reason, pharmaceutical companies are becoming more interested in the potential biochemical properties of tropical species and varieties for developing new drugs. On the basis of data from Costa Rica, Aylward (1993) estimates that the net private returns to pharmaceutical companies prospecting for biological resources are around $4.8 million per new drug per year. Over 50% of these royalty returns could realistically be allocated to biodiversity protection in Costa Rica.

Conserve Ecosystems Through Decreased Environmental Degradation

The improvement of crop and livestock productivity could, in principle, create an environmental advantage. Less land, particularly less marginal land, would need to be cultivated, thereby reducing problems such as soil erosion and desertification and promoting ecosystem conservation. However, this would require more substantial productivity gains than have been achieved thus far with crop cultivars that have been produced through biotechnology and genetic engineering. In addition to high-yield agriculture, biotechnology may produce high-yield forestry, which could not only speed up growth of tree crops such as rubber, pulpwood, and cocoa but would also help preserve rapidly depleting forests (Avery 1993). Although not yet achieved, biotechnology could also help promote environmental management by reducing the use of artificial fertilizers and chemicals and fossil-fuel consumption, which leads to environmental and biodiversity destruction.

Risks

On the other hand, biotechnology and genetic engineering may produce various environmental and social and ethical risks that could ultimately lead to further habitat destruction and depletion of genetic resources. These potential risks include further depletion of biodiversity, harm to nontarget organisms, and exploitation of farmers in developing countries by transnational companies.

Environmental

Further Depletion of Biodiversity

Use of biotechnology could actually lead to the transformation of more land and thus cause the removal of yet more natural ecosystems into agricultural land, which would further deplete biodiversity. For example, the ecosystems of the tropics, where land may not be suitable for agriculture of any kind, may be particularly vulnerable. Encouraging use of certain genetic resources in the production of pharmaceuticals may also lead to a further depletion of biodiversity. Biotechnology and genetic engineering may also favor monocultures and threaten the global centers of ordered biodiversity—the basis for ecological stability, which has already been seriously undermined primarily as a result of global industrialization, urbanization, and overexploitative agricultural practices (Third World Network 1995; Hopkins et al. 1991; Rissler and Mellon 1993).

Harm to Nontarget Organisms

Other environmental risks created through the use of biotechnology and genetic engineering include the ability of genetically engineered organisms to survive and harm nontarget organisms and the creation of new toxic organisms (Goldburg and Tjaden 1990; Jepson et al. 1994). The genetic engineering of viruses and bacteria could lead to the accidental production of toxic or environmentally harmful strains (Greene and Allision 1994). Not all ecological experiments are successful with their potential predictions, and such errors of judgment have had negative effects on the environment in the past.

Socioeconomic

Transnational Companies (TNCs) May Exploit Farmers in Developing Countries

One social concern of biotechnology is that TNCs are building monopolies over transgenic seed production and may eventually disadvantage poor farmers in developing countries (Shiva 1993; Marks et al. 1992). For example, the packaging of seeds with engineered herbicide resistance and the herbicides by agrochemical companies could be viewed in this light (Mannion 1995). The situation is made even more complex because the majority of the genetic resources, and thus biodiversity, on which biotechnology depends are found in developing countries. A second concern is that
because genes extracted from ecosystems in developing nations can be engineered and turned into valuable assets it will be possible for the genes to be patented by developed nations, which will result in developing-world farmers paying for products that originated from their nation's own resources (Shand 1993).

Risk Assessment and Policy Recommendations

If biotechnology is to contribute to sustainable agricultural development, policies must be adopted to ensure that the profit generated by biotechnological research and development is invested in the conservation of the habitats that produced it and that prospecting ventures contribute economic benefits that build technological capacity in the country of origin (Reid 1993). An example that illustrates how this can be done is the partnership between Costa Rica's National Biodiversity Institute (INBio) and Merck and Company, Ltd., by which Merck provides INBio with a $1.1 million dollar budget and INBio provides Merck with plant and animal extracts from biologically diverse, undeveloped areas. In addition, INBio also receives a share of the royalties on any products that are ultimately developed. Mexico, Indonesia, and Kenya are establishing similar bilateral agreements (Reid 1993).

A second way that biotechnology can contribute to sustainable agricultural development is through adoption of an International Biosafety Protocol commissioned by article 19 of the Convention of Biological Diversity (CBD), which was introduced and opened for signature at the Earth Summit meeting in Rio de Janiero in 1992. Because genetically modified organisms (GMOs) are new and may pose novel risks, their future impact on the environment and health is uncertain. Many scientists and organizations, including the authors of this chapter, believe the international community would benefit from a legally binding protocol that sets basic standards for the release and export of GMOs and would prevent further damage to biodiversity and the Earth's ecosystems (Mellon and Rissler 1995; Third World Network 1995; Goldburg 1995; Reid 1993).

Certain nongovernmental organizations (NGOs) have already begun to draft such a protocol. The drafted protocol would require exporters of biotechnology products to submit complete safety information on a case-by-case basis, establish an independent international body of experts to conduct risk assessments and make decisions on all transboundary trade of genetically modified organisms (GMOs), include public participation at every step of decision making, require mandatory labeling for genetically engineered food products, provide technical and analytical support for member countries, and establish liability standards. The protocol also calls for risk assessment to include social and cultural studies and states that genetic diversity "is dependent on the socioeconomic conditions of the peoples maintaining it" (Community Nutrition Institute 1996: 30). However, the United States would most likely only adopt a significantly modified position, that is one that is science-based and within a framework of risk assessment and management that has been proven adequate in the United States, Europe, and elsewhere" (Hoyle 1996).

Certain others in the scientific community do not support the adoption of the CBD and its legally binding International Biosafety Protocol and believe that regulation of biotechnology would serve as a hazard to the diffusion of biotechnology in the developing world; stifle the development of certain applications of biotechnology such as those that can assist in toxic waste removal, water purification, and displacement of agricultural chemicals; and would not likely meet the protocol's goal of safety enhancement cost-effectively (Miller 1996).

CONCLUSION

Techniques of biotechnology and genetic engineering, if applied responsibly, have the potential to increase productivity in crops and livestock, control pests, produce new food and fiber crops, and develop effective medicines (Paolelli and Pimentel 1996). Potential environmental and economic benefits from biotechnology include the reduction of fossil fuel in agriculture and forestry through improved nutrient availability in crops and livestock, use of fewer artificial inputs (e.g., synthetic nitrogen fertilizers, insecticides, and fungicides), and more cost-effective and environmentally friendly waste management practices such as bioremediation. If realized, these improvements will help protect ecological systems by reducing habitat degradation (Paolelli and Pimentel 1996). Although biotechnology and genetic engineering can be expected to provide major benefits to agriculture and the environment, risks with the use of this technology should also be recognized.

Environmental risks include: the potential to alter basic interactions in natural ecosystems; create plants that become new weeds; release pest control organisms that evolve resistance or harm nontarget organisms, or both; and deplete biodiversity further. Potential health risks include: the possibility to introduce new allergens into the food supply, increase levels of antibiotic residues in the food supply, increase the prevalence of antibiotic-resistant bacteria, and create new virulent strains of bacteria and viruses. Socioeconomic risks include: the ability of transnational companies (TNCs) to create monopolies and exploit farmers in developing countries. Ethical risks include issues related to the inhumane treatment of animals and conflicts arising in value and belief systems of certain individuals and organizations.

The public appears to find certain applications of biotechnology and genetic engineering acceptable, including plant-to-plant gene transfers and use of this technology to solve food problems in developing countries. However, other applications of biotechnology, such as animal-to-plant gene exchanges are reported to be less acceptable. The majority of consumers across international borders support mandatory labeling of genetically engineered foods. Because the goal of biotechnology is to reduce rather than increase risk in the food supply, a more effective international regulatory policy is needed. Adoption of an International Biosafety Protocol, as commissioned by article 19 of the Convention on Biological Diversity (CBD), would help reduce the new and novel risks associated with the use of biotechnology and genetic engineering.
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