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ECOLOGICAL ASPECTS OF GENETIC ENGINEERING IN AGRICULTURE AND SOCIETY

by

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Ecological Aspects of Genetic Engineering in Agriculture and Society

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ABSTRACT

Genetic engineering offers many opportunities for improving agriculture and public health. This technology is a major step beyond classical plant and animal breeding and permits the rapid transfer of genetic traits between entirely different organisms. Potential benefits include higher crop and livestock yields and reductions in pesticide and fertilizer use. However, some releases of genetically engineered organisms offer significant threats to the environment, economy, and society.

Already there have been several cases of mismanagement of releases of genetically engineered organisms and one of these releases appears to have had negative public health effects. Because many ecological niches are not filled in natural communities, there is little chance that some invasions of released organisms will not become established.

Once a genetically engineered organism is released and it becomes a pest, the chance of exterminating it is extremely rare. For example, in the United States the only pests that have been exterminated have been the medfly and citrus canker. Of course, both have re-invaded the United States again.

Based on past experience, predicting the ecological effects of releasing genetically engineered organisms depends on the specific organisms, the type of genetic information introduced, and the particular ecosystem into which it is released. No currently devised protocols can be 100% effective in preventing environmental disasters. However, more and better regulations would help reduce the environmental risks of releasing genetically engineered organisms.

INTRODUCTION

Genetic engineering, recombinant DNA (R-DNA) technology improves the opportunities to produce better crop plants and livestock for agriculture.

Thus far, the technology has had little or no impact on increasing the productivity of agriculture, but there is hope that the technology will make important contributions in the future.

Potential benefits of genetic engineering include higher crop and livestock yields and enhanced nutritional value from crops and livestock, reduced pesticide and fertilizer use, and improved control of soil and water pollutants. Nevertheless, dangers exist with the use of genetic engineering. The new genetically engineered organisms may be harmful, by either being "aggressive" and replacing existing organisms and/or becoming pests themselves. Also, genes may "escape" into cultivated or wild species with potential detrimental effects.

Without genetic engineering, humans have by selective breeding, improved and greatly altered crop plants and livestock for agricultural purposes. Some of those species used in agriculture today bear little resemblance to their original wild ancestors. This has been accomplished in some cases with little and other cases with major impact on the ecosystem (Pimentel et al., 1989).

Some crops and animals introduced for agricultural purposes have become serious pests (Pimentel et al., 1989). In general, the greater the alteration of the crops and livestock for agriculture, the less the chance for persistence in the new ecosystem and the organism becoming a pest. However, there are exceptions to this (Pimentel et al., 1989).

In this paper, we assess the potential benefits of genetic engineering and risks of deliberately releasing genetically engineered organisms into the environment. Also, we suggest some approaches and protocols that might be used to minimize the ecological risks associated with the use of genetically-engineered organisms in agriculture.

ENGINEERING CROPS FOR RESISTANCE

Crop resistance to pests. Engineering crop resistance to insect and plant pathogen pests offers advantages to reduce the use of insecticides and fungicides in crop production. This will generally reduce problems from pesticides (NAS, 1988) and improve the economics of pest control (Pimentel, 1986a). Although crop resistance to pests generally offers environmental benefits, care must be exercised to avoid breeding toxic chemicals like alkaloids into the crop or reducing the nutrient makeup of the crop (Pimentel et al., 1984).

Herbicide resistance in crops. Genetically engineering herbicide- resistant crops has the advantage of expanding the array of herbicide types for weed control (NAS, 1987b). In some instances, herbicide resistance may make the use of a more effective herbicide possible, thus reducing the number of herbicide applications. However, engineering resistance to the newer "low-dosage" herbicides will not necessarily reduce environmental hazards (Pimentel, 1971; House et al., 1987; NAS, 1987c). Also, there is a danger that increasing the number of herbicide-resistant crops will encourage wider herbicide use and will contribute to environmental problems.

ECOLOGICAL ISSUES

Potential Changes and Movement

Genetic transfer. Bacteria are capable of transferring novel DNA sequences to bacteria of other species and genera (Stotzky and Babich, 1984, 1986; Marx, 1987). Although these transfers are rare in nature (Slater, 1984; Schofield et al., 1987; Selander et al., 1987a; Trevors et al., 1987), the potential for transfer from engineered organisms designed for persistence in the environment is disconcerting (Stotzky and Babich, 1984, 1986; Strauss et al., 1986). For example, transconjugant bacteria that received "well-characterized" plasmids have demonstrated "unexpected alterations" in chemical makeup, virulence, and antibiotic resistance (Stotzky and Babich, 1984).

Moreover, genetic exchange may occur between closely related plants as well as in microorganisms. For example, important weed species have originated through the hybridization of two intrageneric species, such as the crosses of _Raphanus raphanistrum_ x _sativus_ (radish) and _Sorghum halepense_ (Johnson grass) x _bicolor_ Sorghum corn (Colwell et al., 1986).

Potential evolutionary changes in released organisms. An engineered organism may be genetically unstable (Lindow, 1983a; Halvorson et al., 1985). Also, the additional genetic "baggage" may put the engineered organism at a competitive disadvantage to the unaltered organism in its native habitat (Alexander, 1985; Hartl, 1985). In most cases, genetic and/or ecological instability are likely to result in the exclusion of the engineered organism, but there is always a possibility that the added genes will be favored by natural selection, allowing the organism to become a pest (Alexander, 1985). Such genetic and ecological changes have occurred in native as well as accidentally introduced species like the European corn borer (Brindley and Dicke, 1963; Brindley et al., 1975).

Single gene changes and pathogenicity. Most single gene changes may not adversely affect the pathogenicity and virulence of an organism in the environment (NAS, 1987a). Some gene changes, however, 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). Genetic change has transformed a microbe from being commensal with its plant or animal host to one being pathogenic (Javier et al., 1986; Leonard, 1987; Selander et al., 1987b). For instance, two avirulent herpes simplex viruses were found to be lethal recombinants

(Javier et al., 1986). In addition, a limited host range pathogen of grape was converted to a wide host range strain when gene 4 was transferred to it (Kerr, 1987). Also, some oat rust microorganisms, initially nonpest genotypes for the oat host, became serious pest genotypes after a single gene change allowed the rust to overcome resistance in the oat variety (Van der Plank, 1968; Browning, 1974). This phenomenon has led plant pathologists to develop the "gene-for-gene" principle of parasite-host relationships, where a single mutation in a parasite overcomes single-gene resistance in the host (Person, 1959; Sidhu, 1975; Burdon, 1987; Christ et al., 1987).

Support for the principle that small genetic differences can be ecologically important was provided by Brenner's (1984) conclusion that Escherichia coli, the generally commensal species found in human digestive tracts, and all described species of Shigella could be considered one species on the basis of DNA similarity. Shigella, however, is invariably pathogenic, and Shigella dysenteriae was responsible for an epidemic of dysentery in Mexico and Central America in which 500,000 cases were reported with a fatality rate as high as 35% (Sharples, 1983).

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 toxic insecticides (Gallun, 1977; Roush and McKenzie, 1987). At least 447 species of arthropods have developed resistance to pesticides (Roush and McKenzie, 1987).

Dangers from modified native organisms

Lindow (1983b) reported that there is little or no danger from the ice-minus strain of Pseudomonas syringae, because Ps is a native organism that produces related phenotypes in nature. Just because an organism is a native species, however, does not make it safe for genetic modification and release into the environment. For example, about 60% of the major insect pests of U.S. crops were once harmless native organisms (Pimentel, 1987). Many of these moved from benign feeding on natural vegetation to destructive feeding on introduced crops. The Colorado potato beetle moved from feeding on wild sandbur to feeding on the introduced potato (Casagrande, 1987). This beetle has become a serious pest, and has subsequently encouraged the heavy use of insecticides.

Similarly, nearly half of the major weed species in U.S. agriculture are native plants that have invaded crop habitats (Pimentel, 1987). About 30% of the plant pathogens on U.S. crops are native microorganisms that are also parasitic on native vegetation (Pimentel, 1987). Therefore, because some native organisms have the ability to alter their interactions within an ecosystem, native organisms are not necessarily harmless to agriculture.

Dispersal and movement. The natural dispersal of a pest organism in the environment depends on many factors (Andow, 1986). For example, the westward movement of Dutch elm fungus from the east coast of the United States has been relatively slow due to prevailing westerly winds. These winds have impeded the movement of both the European and American bark beetles, carriers of the Dutch elm disease fungus (Sinclair and Campana, 1978). Conversely, wind aids the potato leafhopper and the true armyworm dispersions each spring from the southern United States to crops in the Northeast and Midwest (a distance of about 2,500 km) (Metcalf et al., 1962; McNeil, 1985).

Microorganisms, including plant pathogens, are also dispersed by wind. For instance, a population of Bacillus has been carried by wind from points of the Black Sea to Sweden (1,800 km) (Andow, 1986), and wheat stem rust is transported approximately 2,500 km northward each year in the United States (Roelfs, 1985).

Once a modified organism is released, therefore, its dispersal will be difficult to monitor effectively and to control. In fact, only two microorganisms have been controlled after introduction: the human disease organism, smallpox, and plant pathogen, citrus canker (reintroduced in 1984) (Civerolo, 1988). The only macroorganism that has been exterminated from the U.S. after introduction has been the Mediterranean fruit fly (Hagen et al., 1981). The "medfly" has been exterminated five times from Florida, once from Texas, and once from California.

Chances for Environmental Hazards

Probability of environmental risks. The probability of an environmental problem occurring after a single release of any engineered organism cannot be accurately predicted at this time. Some ecologists and genetic engineers suggest the risk is low (Alexander, 1985; NAS, 1987a; OTA, 1988). Successful early releases may lead to public confidence that R-DNA organisms are risk-free. Nevertheless, as the number of releases grows, the probability of a problem occurring will increase if public confidence leads to relaxation of the protocols. Also, widespread releases in diverse habitats of genetically engineered organisms will very likely increase the chances of a problem occurring. Commercialization and large-scale use will also increase the probability of encountering problems.

One might also expect the potential environmental problems caused by the release of genetically engineered organisms to vary widely in severity. Experience has shown that exotic organisms have a wide range of impacts on native ecosystems. Consider, for example, the difference between (i) the displacement of the native Hawaiian talitrid sandhoppers by an exotic amphipod sandhopper species, *Talitroides topitotum* (Howarth, 1985), and (ii) the devastating impact on trees and shrubs and in the eastern United States from the introduced European gypsy moth (Cameron, 1986).

Although the public appears willing to accept a risk of 1 chance in 1000 for the occurrence of an environmental problem (OTA, 1987), one release could result in an environmental disaster that could rapidly change the public's attitude towards genetic engineering (Halvorson et al., 1985; Panem, 1985).

In spite of the rigorous U.S. Government Plant and Animal Quarantine program and the low survival rate of introduced foreign organisms, some pest organisms have become established here (Pimentel, 1987). Recent examples are the reintroductions of the Mediterranean fruit fly into California during the summers of 1987 and 1988 (Holmes, 1987). The last medfly eradication effort in California required applying massive amounts of insecticides, costing the government and farmers a total of $174 million (Jackson and Lee, 1985). Major pests also cost the United States $64 billion annually in crop and livestock destruction, despite the annual application of approximately 500,000 tonnes of pesticides (Pimentel, 1986b).

The potential costs of damage resulting from a new pest introduced via genetic engineering, or other causes, can be estimated from data on some current U.S. pests. For example, corn rootworms cost the United States about $2 billion annually (calculated from Schwartz and Klassen, 1980; Pimentel and Levitan, 1986; USDA, 1986). Similarly, the European gypsy moth causes an estimated $100 million in damage to ornamental trees and shrubs, and commercial forests, and costs the United States an additional $10 million in control each year (Pimentel, unpublished).

Intentional introduction of crop plants and animals. Some proponents of R-DNA technology suggest that the intentional introduction of foreign plants and animals into the United States is a good model for predicting potential problems from genetic engineering (NAS, 1987a). If so, there is reason for concern since some serious problems have resulted from the intentional introduction of what were believed to have been beneficial organisms. Moreover, the genetic similarities between many 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 globe (Colwell et al., 1985). In the United States, for example, 125 species of agricultural and ornamental crop plants have become pest weeds out of a total of 5,800 introduced crops (Tables 1 and 2).

Furthermore, 9 out of a total of 20 introduced domestic animal species in the United States have displaced or destroyed native species and, in general, have become serious environmental pests (Tables 2 and 3). Similarly, a total of 5 introduced fish species have become pests (Tables 2 and 3). Of an estimated 2,000 fish species that have been introduced and cultured (McCann, 1984), 104 species have been detected in streams and lakes in the continental United States and 41 species have become established, 16 of which have expanding populations (Courtenay et al., 1984). Although many of these established species have not been declared "pests," there is evidence that many are displacing native species (Table 3). Ten other introduced mammal species, including the mongoose, wild boar, as well as four birds, have also become serious pests (Table 3). It is important to note, however, that while a few biocontrol agents became pests in the early 1800s and 1900s, greater ecological knowledge and established regulations have minimized the environmental impact of the more recent introductions (Pimentel et al., 1984).

This history suggests that the introduction of foreign organisms in the environment could have a major negative impact on many of the 200,000 beneficial plant and animal species in the United States (Pimentel et al., 1980).

Predicting ecological effects. An important step in identifying the environmental problems associated with R-DNA technology is predicting the potential ecological effects of releasing an engineered organism on a case-by-case basis (Andow et al., 1987). Ecologists can predict with a high degree of accuracy the survival rate and interrelationships among some species populations in some environments. For example, insects introduced from the humid tropics have 1 chance in 10 of surviving in most ecosystems of temperate Europe and North America (Williamson and Brown, 1986). Ecologists can also predict with nearly 100% certainty that a pest insect introduced from Europe will become a pest in the United States if the crop it feeds on in Europe is also widely grown here (Metcalf et al., 1962). However, ecologists cannot presently predict with the same degree of accuracy the ecological impacts of all released organisms. For example, of the 212 introduced insects that have become major pests in the United States, 65% were nonpests in their native ecosystems (Calkins, 1983). In these cases, predictions based on the ecology of the insects in their natural habitat would have been inaccurate.

Many scientists suggest that each engineered organism be evaluated individually, prior to release, focusing on the ecology of the unaltered organism and on the proposed release environment (Stotzky and Babich, 1984, 1986; Simberloff, 1985; NAS, 1987a). Clearly, as more information becomes available on the environment and on the biology of each species, greater accuracy in ecological predictions will become possible.

Ecological niches. An estimated 1,500 exotic insects have become established in the United States with a few (17%) becoming pests or having an impact on native species (Sailer, 1978) (Figure 1). This demonstrates that few of the niches in natural ecosystems are filled (Simberloff, 1981; Walker and Valentine, 1984; Colwell et al., 1985; Herbold and Moyle, 1986), and there is ample opportunity, therefore, for many new species to become established in the United States. Thus, although the argument that engineered organisms will not become established due to competition with native species may apply in some cases, it is not always valid (Halvorson et al., 1985).

Preservation of Biological Diversity

Economic value of biological diversity. There are many economically valuable species of plants, animals, and microorganisms. Uncultivated wild plants, for example, contribute raw materials for drugs, medicinals, and other items worth $40 billion per year in the world pharmaceutical market (Myers, 1983). The crop germplasm used by plant breeders in improving crop varieties has been estimated to result in an increase in the value of U.S. crops by about $1 billion annually (Duvick, 1984). Naturally occurring microbes with unexpected abilities to degrade man-made chemical pollutants have also recently been identified (Omenn and Hollaender, 1984; Roberts, 1987). Furthermore, introduced predatory and parasitic insects save California agriculture alone nearly $1 billion per year (van den Bosch et al., 1982).

Due to worldwide habitat destruction, however, biological diversity is rapidly decreasing, with species extinctions occurring at a rate of approximately 1 per day (Myers, 1983). The advent of R-DNA technology offers some hope for the preservation of biological diversity since the ability to extract genetic information from virtually any organism enhances the economic value of diversity (Brill, 1979). However, patents on some genetically engineered organisms will inhibit the use of some germplasm for development of other varieties, thus tending to restrict genetic diversity (Sorrells, 1988). In addition, the possible displacement of native species by released genetically engineered organisms may reduce biological diversity in the ecosystem.

Preservation of genetic diversity in agriculture. Traditional plant breeding techniques have dramatically reduced genetic diversity in most crops (NAS, 1972). Unfortunately, this genetic uniformity has increased crop vulnerability to insect pests, diseases, and climatic fluctuations (NAS, 1972). Genetic engineering, however, may potentially increase the diversity of crop plants through improved gene transfer, and through germplasm screening and selection techniques (Barton and Brill, 1983; Hansen et al., 1986). Although most projects at this time involve single gene transfers into crop plants, the feasibility of multiple gene transfers is expected to improve (Barton and Brill, 1983). Yet, some scientists suggest that genetic diversity in crops may not be achieved, and that long-term sustainability in agriculture will be reduced (Hansen et al., 1986). One of the reasons for this is that every farmer desires to culture the highest-yielding new crop variety.

The difficult ethical choices facing the research establishment are illustrated by the work on transferring the *Bacillus thuringiensis* (Bt) endotoxin into a number of crop plants to kill caterpillar pests (Vaeck et al., 1987). If the current plans for the use of Bt in crops are implemented, pest insects will be exposed to continuous high levels of the toxin over several crops, causing strong selection for resistant genotypes (Gould, 1988). This resistance could be avoided, however, by producing crops that express the Bt toxin "only at times and in places where it is required" (Gould, 1988). Linking the gene for the endotoxin with tissue-specific promoter sequences, for example, would be one way to protect the valuable parts of the crop plant, while leaving a susceptible "refugia" within the crop (Gould, 1988). These procedures, however, would be technically more challenging and perhaps more costly to implement.

PUBLIC POLICY ISSUES

Risks of Mismanagement

In order to realize the potential benefits of R-DNA technology, efforts must be made to prevent mismanagement. The 1987 NAS report ("Introduction of Recombinant DNA-Engineered Organisms into the Environment: Key Issues") has been criticized for including misleading summary statements (Colwell, 1988) and has been said to be "particularly lacking in ecological perspective"

(Mellon et al., 1987). If the new technology is not carefully managed, however, substantial setbacks for the entire industry will occur. For example, after the Three-Mile Island disaster, the entire nuclear industry lost credibility because of mismanagement at one Pennsylvania facility (Bignell and Fortune, 1984). This accident resulted in the adoption of stricter regulations and the return to more expensive energy sources. Disasters (e.g., Bhopal, Challenger, and Chernobyl) in any heavily technological field can result in hostile public perceptions of advanced technologies (Slovic, 1987). Unfortunately, several cases of mismanagement have also been recently associated with genetic engineering.

Mismanagement of a live vaccine developed for swine. A furor arose in 1986 when the USDA approved the use of a genetically engineered, live-virus pseudorabies vaccine without following its own established approval procedures (Volkmer, 1986). First, the developer did not receive permission to field test the vaccine as required by the National Institutes of Health Recombinant DNA Committee. Second, the USDA neglected to classify the vaccine as a "recombinant organism"; finally, the USDA did not follow its own licensing procedures.

Although tests of this particular live-vaccine have subsequently indicated that it is safe for swine and other mammals, some live vaccines for livestock may present environmental and public health problems. Microbes used in vaccine production, for example, can cause injury or death to humans and domestic animals (Krugman and Giles, 1971; Meyer et al., 1971). This has been demonstrated with both the live-vaccine polio virus and the rabies virus used in humans (Fenje, 1971; Melnick, 1971; Bijok et al., 1985). Thorough tests and meticulous care in following regulations, therefore, are necessary to prevent genetically engineered, live-microbe vaccines from causing the very diseases they are supposed to prevent.

Failure to obtain Argentine government approval. A rabies vaccine developed by the Wistar Institute of Philadelphia was tested in cattle in July 1986 by the sponsor, the Pan American Health Organization (PAHO) (Science, 16 January 1987, p. 276). However, PAHO failed to obtain Argentinian government approval for the trial, and the experiment was halted in November 1986. Some public health effects appear to have resulted from this release and these are being investigated (Goldstein, 1988).

Illegal testing of the ice-minus bacterium. During the spring of 1986, Advanced Genetic Sciences tested an ice-minus strain of *Pseudomonas syringae* (Ps) in trees outside before receiving approval from the Environmental Protection Agency (EPA) (Rogers et al., 1986; Crawford, 1987). Ps is an important plant pathogen infecting 17 crops in California (Lindow, 1982) and more than 100 species of wild plants (Lindow et al., 1978). Clearly, under these circumstances, tests in contained environments would be advisable to demonstrate that the modified strain was nonpathogenic to both crop and wild plants (Pimentel, 1987).

Release without approval. More recently, a professor at Montana State University claimed to have released a genetically altered strain of *Pseudomonas syringae* for control of Dutch elm disease without receiving prior approval from EPA (Holdren, 1987). Although the strain was later determined not to be an R-DNA strain, the professor's procedure introduced Dutch elm disease (in violation of the law) to Bozeman, Montana, a region previously free of this disease. While such irresponsible behavior is certainly not common in the scientific community, this incident demonstrates the need for clear and enforceable regulations (see Regulations section).

Socioeconomic Benefits and Costs

Socioeconomic benefits. Genetic engineering is capable of significantly improving yields and enhancing the efficiency of crop and livestock production in the coming decades (NAS, 1987b). These can be accomplished by increasing the proportion of a crop that can be harvested, and by enhancing a crop's tolerance to various stresses. For example, modified *Pseudomonas syringae* may reduce the susceptibility of certain crops to frost and, therefore, allow early planting. Similarly, nitrogen availability, a limiting factor in crop production, could be enhanced through R-DNA technology. Crops like corn and wheat might eventually be modified to "fix" their own nitrogen directly from the atmosphere, potentially saving the nation about $4 billion annually in fertilizer costs (Pimentel, 1987).

In addition, organisms engineered to control pest insects, weeds, and plant pathogens could aid in reducing the more than $64 billion, or about 37%, loss of United States crop production due to pests (Pimentel, 1986a). These modified organisms may potentially reduce a portion of the $3 billion spent on pesticide applications that not only destroy beneficial natural enemies, but cause other environmental, public health, and social problems (Pimentel, 1987).

Socioeconomic costs. In contrast to the benefits of genetic engineering, significant social costs may be incurred (Nader, 1986; Krimsky, 1987). For example, higher crop yields will benefit consumers by providing lower food prices, yet farmers' profit margins will generally decline. On average, for most crop and livestock products, a 1% increase in yield results in a 4.5% decrease in market price received by farmers (Sisler, 1988). This relationship can be illustrated with the case of bovine growth hormone (BGH).

Genetically engineered BGH has the potential to increase milk production in dairy cattle by as much as 40% (field estimates are closer to 10-25%)

(Rauch, 1987). This hormone is currently under consideration for approval by the U.S. Department of Agriculture (USDA) and the Food and Drug Administration (FDA). If put into use, BGH will dramatically increase milk production in the United States at a time when government purchases of surplus milk are up to 12.3 billion pounds per year (Rauch, 1987). The expected 10% to 15% decrease in milk prices will probably further reduce the number of U.S. dairy farmers (Kalter and Milligan, 1988). All evidence suggests, therefore, that the use of BGH will accelerate the trend toward fewer and larger farms in the United States (Buttel, 1988; DuPuis and Geisler, 1988) and contribute further to the loss of cultural diversity in an increasingly urban society (Coen et al., 1987).

The potential effects of genetic engineering on rural land use have yet to be assessed. This rapidly advancing technology is, however, clearly capable of causing major ecological, economic, and social changes. Small farmers in developing countries, for example, may experience severe negative effects. Using microbes to produce synthetically cocoa, coffee, and tea extracts from relatively simple carbohydrates may eventually lead to the elimination of these industries in developing countries (Buttel and Barker, 1985). For countries like Ghana, where more than 20% of the workforce is employed in cocoa production, this new technology could create major economic and social problems, in addition to stimulating potentially unprecedented and environmentally destructive land use change (Christian, 1985). Due to the increasing significance importance of international trade, financial crises in developing countries can affect the economies of the developed world. This was clearly demonstrated in 1973-74 when increases in oil prices caused U.S. grain exports to decline 50% (USBC, 1987).

Ethical issues. A highly competitive and secretive climate currently surrounds most genetic engineering research in the United States (Buttel et al., 1985). The financial rewards for successful research are enormous. However, these incentives are unlikely to encourage innovation aimed at providing the greatest humanitarian good (Buttel et al., 1985). For this reason, a stronger public role in defining and supporting key research objectives, and in formulating standards to regulate the industry, is needed to temper the substantial influence of private enterprise on the development of R-DNA technology. If germplasm, including genes such as those coding for Bt endotoxins, could be considered a natural resource (NAS, 1978), government involvement would be justified to protect these resources (Gould, 1988).

Regulation of R-DNA Technology

Government regulatory agencies. In June 1986, the federal government established guidelines for regulating the genetic engineering industry, in addition to creating an interagency system known as the Coordinated Framework for Regulation of Biotechnology (Federal Register, 1986). Responsibility for controlling the safety of new products is now divided among five federal agencies: (1) the USDA is responsible for engineered organisms used with crop plants and animals; (2) the FDA is responsible for genetically engineered organisms or their products in processed foods and drugs; (3) the National Institutes of Health (NIH) is responsible for engineered organisms that could affect public health; (4) the Occupational Safety and Health Administration (OSHA) is responsible for engineered organisms that may affect the workplace; and (5) the EPA is responsible for engineered organisms released into the environment for pest and pollution control and related activities (Committee on Science and Technology, 1986).

Divergent views exist regarding the merits of industry regulation. Some believe these divisions of authority are cumbersome (Young and Miller, 1987;

Fox, 1988), and others propose the abolishment of all the regulations (Szybalski, 1985). Yet, some argue that regulation actually assists the development of biotechnology (Gibbs and Greenhalgh, 1983).

Agencies such as the USDA, which both promote and regulate this new technology, may be faced with a conflict of interest. The same combination of promotion and regulation did not work when the USDA was responsible for regulating the use of pesticides, and eventually control was transferred to the EPA (GAO, 1986). NIH has provided sound guidelines for laboratory research dealing with genetic engineering, but it is not a regulatory agency and, therefore, its only means of control is to seek EPA's help in regulation. EPA, however, is attempting to regulate genetically engineered organisms under the Toxic Substances Control Act, but TSCA has serious deficiencies (Schiffbauer, 1985). It is extremely important, however, that fairness and effectiveness be achieved in regulatory policy (Nourish, 1983; Coulson and Soper, 1984; Committee on Energy and Commerce, 1985; Committee on Science and Technology, 1986).

Socioeconomic evaluation. The benefits and costs of R-DNA technology to society should be rigorously assessed. An attempt should be made to balance potential short-term benefits (private and public) with possible long-term costs. Given this technology's potential social, economic, and environmental impacts, a prudent approach in minimizing these risks is needed. Public policies must cautiously yet fairly regulate R-DNA technology research and development.

Testing protocols. When establishing testing protocols, it is important to remember that the biotic and chemical interactions in nature are much more complex than those produced in laboratory tests. At this time, the safest approach is to include tests at progressively more complex levels of ecosystem structure (OECD, 1988). We propose the following steps: (1) conduct laboratory microcosm tests to improve the understanding of the engineered organism; (2) carry out small plastic-enclosed ecosystem field tests; and (3) conduct small-scale field tests.

Monitoring. Developing the means for tracking genetically engineered microorganisms is essential if the fate of these organisms in nature is to be determined. The monitoring methods must be specific, convenient, reliable, and sensitive (Omenn, 1986). Currently, the six major monitoring methods include: (1) selective media; (2) resistance to particular antibiotics; (3) immunofluorescence techniques; (4) DNA genetic probes; and (5) R-DNA finger printing (Mallory et al., 1982; Omenn, 1986; Levin et al., 1987; Marx, 1987); and (6) serological tests. To date none of these is completely reliable or sufficiently sensitive; however, if more than one were employed some of the deficiencies might be reduced.

Control of problem releases. Various procedures are suggested to control problems that might develop if engineered organisms are released into the environment. Some engineered organisms, like plants in pots, can be collected and destroyed relatively easily; however, others are more difficult to contain. Some microbes and macroorganisms, for example, disperse rapidly (Andow, 1986). Others, like pox viruses, are extremely difficult to control by any technique (Goldstein, 1988). Past experience demonstrates that effectively controlling a released organism is extremely difficult. Furthermore, the record worldwide is poor for exterminating introduced pests after introduction (DeVos et al., 1956; Elton, 1958; Laycock, 1966; Joenje, 1987).

CONCLUSIONS

Genetic engineering is expected to have many benefits in agriculture and public health. As with many new technologies, however, there are socio-economic and environmental problems associated with R-DNA technology. Never before have we had the opportunity to transfer genetic traits between totally different microbes, plants, and animals. This ability presents unique risks to the environment, not unlike the problems created by introduction of exotic species. With only six field releases to date, we have little information or experience concerning potential environmental risks. As is common when there are insufficient data, wide-ranging speculations and many misconceptions exist.

Based on our analyses, we conclude that:

(1) Developing crops resistant to pests has minimal risks and should help reduce pesticide use.

(2) Although engineering herbicide resistance in crops may increase herbicide efficiency in some instances, this approach will potentially encourage the use of a wider array of herbicides on a variety of crops -- thus intensifying ecological problems associated with these pesticides.

(3) While genetically engineered microbes released to attack specific chemical pollutants have the potential to improve the environment, these microbes must be compound-specific and produce harmless by-products; if not, they may pose environmental hazards.

(4) When unique genetic characters are released into the environment via microbes and other organisms, a few of these novel DNA sequences may be transferred to other microbes and other organisms.

(5) Some single gene changes may convert a benign organism into a serious plant or animal pathogen.

(6) Because most pest species are of native origin, the use of native organisms to genetically engineer new organisms is not necessarily without risk.

(7) Few ecological niches in the ecosystem are completely filled; therefore, natural communities are unlikely to resist invasion by foreign organisms, including genetically engineered organisms.

(8) Based on past experience, the chance of an intentional foreign plant or animal introduction becoming a pest in the United States ranges from 1 in 10 to 1 in 100.

(9) R-DNA technology has the potential to increase genetic diversity in agriculture and forestry; however, due to numerous factors in development and use of crop and forest varieties, genetic diversity in these systems is expected to decline.

(10) Accuracy in predicting the ecological effects of releasing a genetically engineered organism depends on the specific organism, the type of genetic information introduced, the particular environment into which it is released, and the availability of detailed ecological information.

(11) Insufficient data exist to forecast environmental problems and pest outbreaks resulting from the release of genetically engineered organisms. Based on the data presented, we expect some environmental problems to occur because: (i) none of the test protocols will allow us to predict with 100% accuracy the impact of altered organisms on the environment; (ii) in the past, we have been unable to distinguish with total accuracy beneficial organisms from potential pests; (iii) a large number of releases into the environment increases the probability of a hazardous introduction; and (iv) the dangers caused by human error can never be eliminated.

(12) Several incidents have already demonstrated mismanagement of genetic engineering technology. A clear need exists, therefore, for more effective regulation and management of this technology.

(13) To achieve efficient, effective regulation, genetic engineering should be regulated only by EPA and OSHA; however, EPA should not attempt to carry out regulation under TSCA.

(14) The socioeconomic costs and benefits of genetic engineering technology must be assessed to determine beforehand who the gainers and losers will be.

Genetic engineering offers many opportunities for improving agriculture and public health. However, we believe the risks of this new technology must be recognized and effectively managed. Failure to exercise caution could lead to serious environmental, economic and social problems in the United States and in all other nations. Although momentum is building for immediate results, the impact of potential problems on public confidence in the technology could delay, or jeopardize, the realization of the potential benefits from genetic engineering.

Table 1. Agricultural and Ornamental Plant Introductions that became Pest Weeds in the United States

Plant Introduced	Purpose of Introduction	Weed Problem	Sources
Johnsongrass *Sorghum halepense* (L.) Pers.	Forage	Crops, Pastures	McWhorter (1971); Williams and Hayes (1984)
Mississippi Chicken Corn (shatter cane) *Sorghum bicolor* (L.) Moench	Grain	Grain Crops	DeWet and Harlan (1975)
Goatsrue *Galega officinalis* L.	Forage	Crops, Pastures	Williams (1980)
Crotalaria *Crotalaria spectabilis* Roth *Crotalaria retusa* L.	Forage and Green Manure	Soybeans, Rangelands	Patterson (1982)
Sicklepod milkvetch *Astragalus falcatus* Lam.	Forage	Rangelands	Williams (1980)
Reed canarygrass *Phalaris arundinacea* L.	Forage	Irrigation Ditches, Canals	USDA (1971)
Bermudagrass *Cynodon dactylon* (L.) Pers.	Forage	Pastures	Brown et al. (1985); Muenscher (1980)
Cogongrass *Imperata cylindrica* (L.) Beauv.	Forage	Crops, Pastures	Patterson et al. (1983)
Bush beardgrass *Andropogon glomeratus* (Walt.) B.S.P.	Forage	Displaces Native Species	Smith (1985)
Broomsedge *Andropogon virginicus* L.	Forage	Displaces Native Plants	Smith (1985)
Kikuyugrass *Pennisetum clandestinum* Hochst. ex. Chiov.	Forage	Displaces Native Species	Smith (1985)
Meadow ricegrass *Microlaena stipioides* (Labill.)	Forage	Displaces Native Grasses	Smith (1985)
California grass, tall panicum *Brachiaria mutica* (Forsk.)	Unknown[1/]	Cultivated Crops Native Habitats and Roadsides Weed	Smith (1985)

Plant Introduced	Purpose of Introduction	Problem	Sources
Haole koa *Leucaena leucocephala* (Lam.) de Wit	Forage	Cultivated Crops	Smith (1985); Haselwood and Motter (1983)
Guineagrass *Panicum maximum* Jacq.	Forage	Cultivated Crops	Smith (1985); Haselwood and Motter (1983)
Molasses grass *Melinis minutiflora* Beauv.	Forage	Wastelands	Smith (1985); Haselwood and Motter (1983)
Kochia *Kochia scoparia* (L.) Schrad.	Forage, Ornamental	Crops, Pastures	Muenscher (1980); Wiley et al. (1985)
Kudzu *Pueraria lobata* (Willd.) Ohwi	Forage and Erosion Control	Forests, Roadways	Hopson (1981); Laycock (1983)
Cordgrass *Spartina anglica*	Forage and Bank Stabilization	Wetland Bird Refuges	Johnson (1985)
Yellow Himalayan blackberry *Rubus ellipticus* Sm.	Fruit	Displaces Native Species	Smith (1985); Neal (1965)
Raspberry *Rubus glaucus* Bth.	Fruit	Displaces Native Species	Smith (1985)
Rubus nivalis Doug.	Fruit	Displaces Native Species	Smith (1985)
Florida prickly blackberry (high bush blackberry) *Rubus argutus* Link	Fruit	Displaces Native Species	Smith (1985)
Guava *Psidium guajava* L.	Fruit	Wastelands and Roadsides	Smith (1985); Neal (1965)
Buffelgrass *Cenchrus cillarus* L.	Cover for Erosion Control	Displaces Native Species	Smith (1985)
Chinese violet *Asystasia gangetica* (L.) T. Anders	Cover Crop	Displaces Herbaceous Cover	Smith (1985); Neal (1965)
Klu (huisache) *Acacia farnesiana* Willd.	Perfume from Flowers	Pastures	Smith (1985); Haselwood and Motter (1983)

Plant Introduced	Purpose of Introduction	Weed Problem	Sources
Hemp or marijuana Cannabis sativa L.	Fiber, Medicine	Pastures	Muenscher (1980)
New Zealand flax Phormium tenax J.R. and G. Forst	Fiber Production	Displaces Native Species	Smith (1985); Neal (1965)
Multiflora rose Rosa multiflora Thunb. ex Murr.	Windbreaks, Cover Plantings	Pastures	USDA (1971)
Gorse Ulex europaeus L.	Hedge for Sheep	Pastures and Rangelands	Smith (1985); Haselwood and Motter (1983)
Opiuma Pithecelobium dulce (Roxb.) Benth.	Hedge Planting	Displaces Native Species	Smith (1985); Neal (1965)
Cats claw Caesalpinia sepiaria Roxb.	Hedge Ornamental	Pastures and Rangelands	Smith (1985); Haselwood and Motter (1983)
Molucca albizia Albizzia moluccana Miq	Forestation	Displaces Native	Smith (1985); Neal (1965)
Mexican ash Fraxinus uhdei (Wenzig)	Forestation	Displaces Native Trees	Smith (1985); Neal (1965)
Melochia Melochia umbellata (Houtt.)	Forestation	Displaces Native Trees	Smith (1985); Neal (1965)
Slash pine Pinus caribaea Morelet	Forestation	Displaces Native Species	Smith (1985); Neal (1965)
Mexican weeping pine Pinus patula Schlecht. and Cham.	Forestation	Displaces Native Species	Smith (1985); Neal (1965)
Juniper berry Citharexylum caudatum L.	Arboretum	Displaces Native Species	Smith (1985); Neal (1965)
Koster's curse Clidemia hirta (L.)	Brought in by Marijuana Growers	Pastures and Rangelands	Smith (1985); Haselwood and Motter (1983)

Plant Introduced	Purpose of Introduction	Weed Problem	Sources
Tansy, common *Tanacetum vulgare* L.	Herb	Gardens, Roadsides	Pammel (1911); Muenscher (1980)
Dyers woad *Isatis tinctoria* L.	Dyes	Rangelands, Crops	Aspevig et al. (1985)
Henbane, black *Hyoscyamus niger* L.	Medicine	Roadsides	Williams (1980)
Belladonna *Atropa belladonna* L.	Medicine	Roadsides	Williams (1980)
Melaleuca *Melaleuca* quinquenervia (Cau.) Blake	Afforestation	Wetland Habitats	Williams (1980); Vietmeyer (1986)
Waterhyacinth *Eichhornia crassipes* (Mart.) Solms	Ornamental for Pools	Lakes, Waterways	Penfound and Earle (1948); Pierce (1983); Gopal (1987)
Hydrilla *Hydrilla verticillata* (L.f.) Royle	Ornamental for Aquarium	Lakes, Waterways	Anon. (1984a, 1984a,b)
Brazilian peppertree *Schinus terebinthifolius* Raddi	Ornamental	Forests, Parks, Gardens	Williams (1980); Vietmeyer (1986)
Macartney rose *Rosa bracteata* J.C. Wendl.	Ornamental	Pastures	Williams (1980)
Slender speedwell *Veronica filiformis* sm.	Ornamental	Turf, Lawns	Cisar (1981)
Lantana, large leaf *Lantana camara* L.	Ornamental	Fence rows, Pastures	Elton (1958); Haselwood and Motter (1983)
Dalmatian toadflax *Linaria genistifolia* subsp. *dalmatica* (L.) Maire & Petitmengin	Ornamental	Rangelands	Robocker (1974); USDA (1971)
Japanese honeysuckle *Lonicera japonica* Thunb.	Ornamental	Pastures, Woodlands	USDA (1971); Muenscher (1980)

Plant Introduced	Purpose of Introduction	Weed Problem	Sources
Japanese knotweed *Polygonum cuspidatum* Sieb. & Zucc.	Ornamental	Lowlands, Homesites	Muenscher (1980)
French tamarisk *Tamarix gallica* L.	Ornamental	Pastures, Floodplains	Williams (1980)
Stranglervine *Morrenia odorata* (Hook. & Arn.) Lindl.	Ornamental	Citrus Orchards	Ridings (1985)
Yellow toadflax *Linaria vulgaris* Mill.	Ornamental	Rangelands	USDA (1971)
Bouncingbet *Saponaria officinalis* L.	Ornamental	Pastures	Pammel (1911), Muenscher (1980)
European buckhorn *Rhamnus cathartica* L.	Ornamental	Pastures, Rangelands	Williams (1980)
Chinaberry *Melia azedarach* L.	Ornamental	Pastures, Rangelands	Williams (1980)
Corn cockle *Agrostemma githago* L.	Ornamental	Wheat, Grasslands	USDA (1971); Muenscher (1980)
Foxglove *Digitalis purpurea* L.	Ornamental	Pastures	Muenscher (1980)
Jimsonweed *Datura stramonium* L.	Ornamental	Pastures, Croplands	Muenscher (1980); USDA (1971)
Precatory bean *Abrus precatorius* L.	Ornamental, Medicine	Fence rows, roadsides	Williams (1980)
Purple loosestrife *Lythrum salicaria*	Ornamental	Wetland Bird Refuges, Waterways	USDI (1987)
Black wattle, green wattle *Acacia mearnsii* Willd.	Ornamental	Displacement of Native Species	Smith (1985); Neal (1965)

Plant Introduced	Purpose of Introduction	Weed Problem	Sources
Java plum *Eugenia* *cumini* (L.) Druce	Ornamental and Forestation	Displaces Native Trees	Smith (1985); Neal (1965)
Roseapple *Eugenia* *jambos* (L.)	Ornamental and Forestation	Displaces Native Trees	Smith (1985); Neal (1965)
Chinese banyan *Ficus* retusa L.	Ornamental and Forestation	Displaces Native Trees	Smith (1985); Neal (1965)
Kiawe *Prosopis* *pallida* (Humb. and Bonpl.)	Ornamental and Forestation	Displaces Native Trees	Smith (1985); Neal (1965)
Silk oak *Grevillea* *robusta* A. Cunn.	Ornamental and Forestation	Allelopathy inhibits Native Species	Smith (1985); Neal (1965)
Fountaingrass, Crimison *Pennisetum* *setaceum* (Forsk.) Chiov	Garden	Displaces Native Species	Smith (1985); Neal (1965)
German ivy *Senecio* *mikanioides* Otto ex walp	Ornamental	Rangelands	Smith (1985); Haselwood and Motter (1983)
Palmgrass *Setaria* *palmifolia* (Koen.) Staph	Ornamental	Wastelands and Roadsides	Smith (1985); Haselwood and Motter (1983)
African tuliptree *Spathodea* *campanulata* Beauv.	Ornamental	Displaces Native Trees	Smith (1985); Haselwood and Motter (1983)
Wild Marigold, Stinkweed *Tagetes* *minuta* L.	Ornamental	Pastures and Rangelands	Smith (1985); Haselwood and Motter (1983)
False kamani, Tropical Almond *Terminalia* *catappa* L.	Ornamental	Displaces Native Species	Smith (1985)
Glorybush *Tibouchina* *urvilleana* (DC.) Cogn. Difam	Ornamental	Displaces Native Species	Smith (1985)
Common mullein, Velvet Plant *Verbascum* *thapsus* L.	Ornamental	Displaces Native Species	Smith (1985)
Bamboo *Bambusa* sp.	Ornamental	Impenetrable Thickets	Neal (1965)

Plant Introduced	Purpose of Introduction	Weed Problem	Sources
Common ironwood, Australian-pine *Casuarina equisetifolia* L. ex J.R. and G. Forst.	Ornamental	Displaces Native Species	Smith (1985)
Swamp oak, Scaly-bark beefwood *Casuarina glauca* Sieb.	Ornamental	Displaces Native Species	Smith (1985)
Trumpet tree *Cecropia peltata* Sandmark	Ornamental	Displaces Native Species	Smith (1985)
Bocconia frutescens L.	Ornamental	Displaces Native Species	Smith (1985); Neal (1965)
Fayatree, firebush *Myrica faya* Ait.	Ornamental	Pastures and Rangelands	Smith (1985); Haselwood and Motter (1983)
Octopus tree *Brassaia actinophylla* Endl.	Ornamental	Displaces Native Trees	Smith (1985); Neal (1965)
Fiddlewood *Citharexylum spinosum* L.	Ornamental	Displaces Native Species	Smith (1985); Neal (1965)
Glorybower *Clerodendron japonicum* (Thunb.) Sweet	Ornamental	Pastures and Rangelands	Smith (1985); Haselwood and Motter (1983)
Trailing velvet plant *Rubus moluccanus* L.	Ornamental	Displaces Native Species	Smith (1985)
Formosan koa *Acacia confusa* Merr.	Ornamental	Displaces other plants because of allelopathy	Smith (1985)
Sour bush *Pluchea odorata* (L.)	Ornamental	Displaces Native Species	Smith (1985); Neal (1965)
Strawberry guava *Psidium cattleianum* Sabine	Ornamental	Displaces Native Species	Smith (1985); Neal (1965)
Indian rhododendron *Melastoma malabathricum* L.	Ornamental	Displaces Native Species	Smith (1985); Neal (1965)
New Zealand tea, tea tree *Leptospernum scoparium* J.R. & G. Forst	Ornamental	Displaces Native Trees	Smith (1985)

Plant Introduced	Purpose of Introduction	Weed Problem	Sources
Hairy cats-ear (Spotted cats-ear) *Hypochoeris radicata* L.	Ornamental	Cultivated Crops	Smith (1985); Neal (1965)
Downy rosemyrtle *Rhodomyrtus tomentosa* (Ait.)	Ornamental	Displaces Native Species	Smith (1985); Neal (1965)
Castorbean *Ricinus communis* L.	Ornamental	Pastures and Rangelands	Smith (1985); Neal (1965)
Sweet granadilla, Lemona *Passiflora ligularis* Juss.	Ornamental	Displaces Native Species	Smith (1985); Neal (1965)
Banana poka *Passiflora mollissima* (HBK.) Bailey	Ornamental	Displaces Native Species	Smith (1985); Neal (1965)
Huehue-haole (Corky stemmed passion flower) *Passiflora suberosa* L.	Unknown[1/]	Displaces Native Species	Smith (1985); Neal (1965)
Hilo grass (sour paspalum) *Paspalum conjugatum* Berg.	Unknown[1/]	Displaces Native Species	Smith (1985); Neal (1965)
Red mangrove, American mangrove *Rhizophora mangle* L.	Unknown[1/]	Displaces Native Species	Smith (1985); Neal (1965)
Tree manuka *Leptospernum ericoides* A. Rich.	Ornamental	Displaces Native Species	Smith (1985)
White ginger *Hedychium coronarium* Koenig	Ornamental	Displaces Native Species	Smith (1985); Neal (1965)
Yellow ginger *Hedychium flavescens* Carey	Ornamental	Displaces Native Species	Smith (1985); Neal (1965)
Kahili ginger *Hedychium gardnerianum* Roscoe	Ornamental	Displaces Native Species	Smith (1985); Neal (1965)
White moho *Heliocarpus popayaensis* HBK.	Reforestation	Displaces Native Species	Smith (1985); Neal (1965)
Velvetgrass, common *Holcus lanatus* L.	Ornamental	Displaces Native Species	Smith (1985)

Plant Introduced	Purpose of Introduction	Weed Problem	Sources
Mauritius hemp *Furcraea foetida* (L.) Haw	Unknown[1]	Dense Thickets	Smith (1985); Neal (1965)
Kahili flower, Haiku *Grevillea banksii* R. Br	Unknown[1]	Allelopathy Inhibits Native Species	Smith (1985); Haselwood and Motter (1983)
Linociera *Linociera intermedia* Wight	Unknown[1]	Displaces Native Species	Smith (1985); Neal (1965)
Beggar's tick, Spanish needle *Bidens pilosa* L.	Unknown[1]	Cultivated Crops and Roadsides	Smith (1985); Neal (1965)
Cluster pine *Pinus pinaster* Ait.	Reforestation	Displaces Native Species	Smith (1985); Neal (1965)
Indian fleabane *Pluchea indica* (L.) Less.	Unknown[1]	Pasture and Rangelands	Smith (1985); Neal (1965); Haselwood and Motter (1983)
Glenwood grass *Sacciolepis indica* (L.) Chase	Unknown[1]	Displaces Native Species	Smith (1985)
Sweet vernalgrass *Anthoxanthum odoratum* L.	Unknown[1]	Invades Disturbed Areas	Smith (1985)
Shoebutton ardisia *Ardisia humilis* Vahl	Unknown[1]	Dense Stands Crowd out other species	Smith (1985)
New Zealand laurel *Corynocarpus laevigatus* J.E. & G. Forst.	Unknown[1]	Displaces Native Species	Smith (1985)
Woodrose *Merremia tuberosa* (L.) Rendle	Ornamental	Displaces Native Species	Smith (1985); Neal (1965); Haselwood and Motter (1983)
Triana *Miconia magnifica*	Ornamental	Displaces Native Species	Smith (1985)

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[1] Some of the plants listed here from Smith (1985) may have been accidental introductions; however, the author indicates that most of these were introduced intentionally.

Animal Introduced	Purpose of Introduction	Pest Problem	Sources
Sika Deer *Cervus nippon*	Sport Hunting	Displaced whitetailed deer in some locations	Flyger (1960); Feldhamer et al. (1978); Armstrong and Harmel (1981)
European Red Fox *Vulpes vulpes*	Sport Hunting	Prey on wildlife	DeVos et al. (1956)
Ring-Necked Pheasant *Phasianus colchicus*	Sport Hunting	Displaced prairie chickens in some locations	Sharp (1957); Laycock (1966); Vance and Westemeirer (1979); Robinson and Bolen (1984)
Muscovy Duck *Cairina moschata*	Sport Hunting	Might displace wood ducks or black-bellied whistling ducks	Weller (1969); Bolen (1971)
German Carp *Cyprinus carpio*	Sport Fishing	Muddied lake water, native sport fish	Cole (1904); Threinem and Helm (1954); Robel (1961)
Black Tilapia *Tilapia melanpleura*	Food	Native sport fish	Courtenay et al. (1974)
Starling *Sturnus vulgaris*	Aesthetics, Shakespeare	Faeces and disease	Laycock (1966)
Guppy *Lebistes reticuletus*	Aquarium fish	Displace native fish	Courtenay and Robins (1975)
Spotted Tilapia *Tilapia mariae*	Aquarium fish	Displace native fish	Courtenay and Robins (1975)
Walking Catfish *Clarias betrachus*	Aquarium fish	Native sport fish	Courtenay et al. (1974)
Black Acara *Cichlasoma bimaculatum*	Fish Trade, Aquarium Fish	Native sport fish	Courtenay et al. (1974)
Grass Carp *Ctenopharyn godon idella*	Biological Control of Aquatic Weeds	Native sport fish	Avault (1965); Cross (1969); Pierce (1983)
Blue Tilapia *Tilapia aurea*	Biological Control, Aquatic Plants	Degraded aquatic ecosystem	Courtenay and Robins (1975)

Table 2. Agricultural and ornamental plant introductions and agricultural, sport, and pet animal introductions that became pests[1] in the United States.

Introductions	No. of species for intentional introductions	No. of species that became pests
Agr. & Ornamental		
Plants	5,800 [2]	125
Domestic Mammals & Birds	20 [3]	10
Sport Mammals & Birds	20 [4]	9
Biological Control Vertebrates	5	5
Aquarium & Sport Fish	2,000 [5]	5

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[1] A pest can be narrowly defined as an organism with direct impacts on human welfare, or more broadly defined to include negative impacts on indigenous organisms and habitats. Many of the authors cited used the narrow definition.

[2] Kresovich (1987).

[3] Estimated number of introduced mammals and birds.

[4] Estimated; however, this value does not include 51 exotic species introduced into Texas for game purposes -- none of which to date have been classed as a problem (Armstrong and Wardroup, 1980).

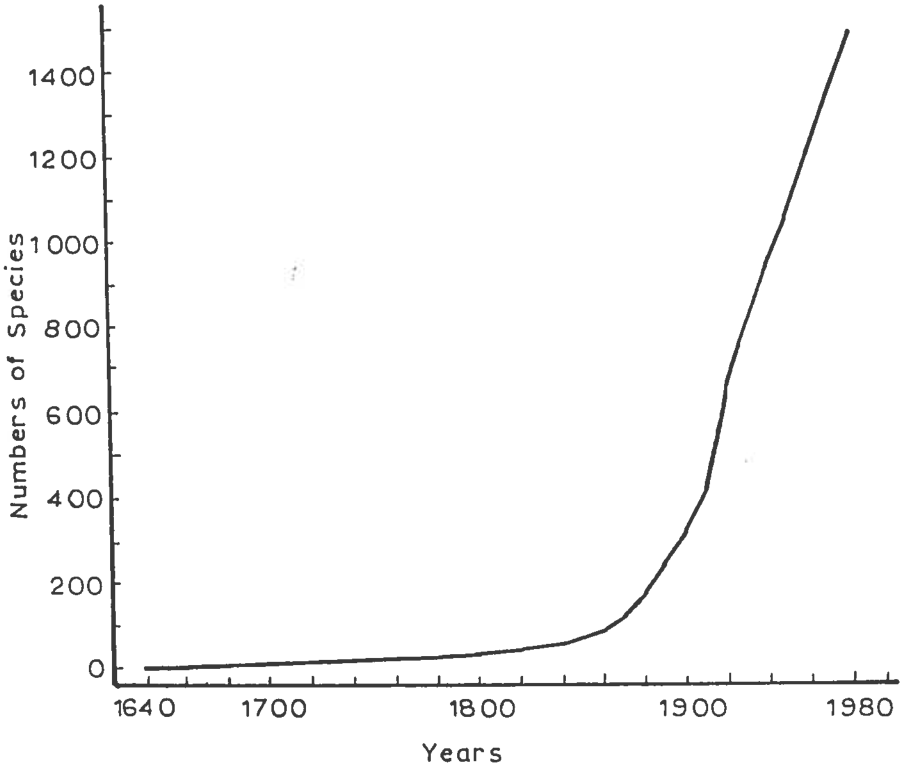
[5] Estimated (McCann, 1984).

Animal Introduced	Purpose of Introduction	Pest Problem	Sources
Indian Mongoose *Herpestes auropunctatus*	Biological Control of Rats	Poultry, native birds and lizards, human diseases	Tierkel et al. (1952); Baldwin et al. (1952); Pimentel (1955); Nellis and Everard (1983)
English Sparrow *Passer domesticus*	Biological Control of Caterpillars	Grain and fruit crops, native birds	Southern (1945); Robbins (1973); Zeleny (1976)
Common Myna *Acridotheres tristis*	Biological Control of armyworms	Native birds	Laycock (1966); Byrd (1972)

Table 3. Agricultural, Sport, and Pet Animal Introductions that Became Pests in the United States

Animal Introduced	Purpose of Introduction	Pest Problem	Sources
Feral Goat *Capra prisca*	Milk, Meat	Forests, shrubs in Hawaii	Roots (1976); Baker and Reeser (1972)
Feral Sheep *Ovis aries*	Meat, Wool	Vegetation destruction in Hawaii and Channel Islands	Roots (1976); Van Vuren and Coblentz (1987)
Feral Pig *Sus scrofa* (domestic)	Meat, Leather	Vegetation destruction in Hawaii	Pimm and Pimm (1982)
Feral Burro *Equus asinus*	Draft Animal	Vegetation destruction	Laycock (1966); Presnall (1985)
Feral Horse *Equus cabllus*	Draft Animal	Rangeland vegetation	McKnight (1964); Presnall (1985)
Feral Cat *Felis catus*	Pet	Prey on wildlife	DeVos et al. (1956)
Feral Dog *Canis familiaris*	Pet	Prey on wildlife	DeVos et al. (1956)
Reindeer *Rangifer tarandus*	Meat, Leather	Rangeland vegetation	Roots (1976)
European Rabbit *Oryctolagus cuniculus*	Meat	Vegetation destruction on Smith Islands	Roots (1976)
European Gypsy Moth *Lymantria dispar*	Silk Production	Forests and ornamentals	Cameron (1986)
European Hare *Lepus europaeus*	Sport Hunting	Crops, orchards	Silver (1924)
Nutria *Myocastor coypus*	Fur	Crops, orchards, drainage canals	DeVos et al. (1956); Schitoskey et al. (1972); Kuhn and Peloquin (1974)
European Wild Boar *Sus scrofa*	Sport Hunting	Crops, forests, wildlife	Stegman (1938); Pines and Gerdes (1973)

3')



1400
1200
1000
800
600
400
200
0
Numbers of Species
1640
1700
1800
1900
1980
Years

Figure 1. Number of species of insects and mites introduced into the 48 contiguous states from 1640 to 1980 (after Sailer 1983).