Center
for the
Study of
American
Business

CSAB

Applying the Precautionary Principle to Genetically Modified Crops

by Indur M. Goklany

Policy Study
Number 157

August 2000

Washington University in St. Louis

Applying the Precautionary Principle to Genetically Modified Crops

by Indur M. Goklany

CENTER FOR THE STUDY OF AMERICAN BUSINESS

Policy Study Number 157

August 2000

This booklet is one in a series designed to enhance understanding of the private enterprise system and the key forces affecting it. The series provides a forum for considering vital current issues in public policy and for communicating these views to a wide audience in the business, government, and academic communities.

The Center for the Study of American Business is a nonprofit, nonpartisan organization funded entirely by grants from foundations, business firms, and private citizens. Funding is unrestricted, enabling researchers to maintain academic freedom and ensuring unbiased and independent research. The Center is an integral part of Washington University, which has been granted tax-exempt status under section 501(c)(3) of the Internal Revenue Code.

Donations can be made to the Center at the following address:

Center for the Study of American Business
Washington University
Campus Box 1027
One Brookings Drive
St. Louis, MO 63130-4899

Contents

List of Figures and Tables

Executive Summary

The precautionary principle has often been invoked to justify a ban on genetically modified (GM) crops. However, this justification is based upon a selective application of the principle to the potential public health and environmental benefits of such a ban, while ignoring a ban's potential downside. This is due principally to the fact that the precautionary principle itself provides no guidance on its application in situations where actions (such as a ban on GM crops) could simultaneously lead to uncertain benefits and uncertain costs to public health and the environment.

Accordingly, I first develop a framework for applying the principle in cases where the final outcome is ambiguous because both costs and benefits are uncertain. Then, based on a brief survey of the public health and environmental costs and benefits of GM crops, I apply this framework to the broad range of consequences of a ban on GM crops. This application of the framework indicates that by comparison with conventional crops, GM crops would increase the quantity and nutritional quality of food supplies. Accordingly, GM crops ensure that—despite the expected increases in human population—the world's progress in improving public health, reducing mortality rates, and increasing life expectancies during the twentieth century should be sustained into the twenty-first.

Plant and animal genes have always been part and parcel of the human diet, and consumption of these genes has not modified human DNA. The public health benefits from GM crops, therefore, are likely to be larger in magnitude and more certain than the adverse public health effects from the ingestion of any genes that may be transferred from various organisms into GM crops.

With respect to environmental effects, cultivation of GM, rather than conventional, crops would be more protective of biological diversity and nature. By increasing productivity, GM crops reduce the amount of land and water that would otherwise have to be converted to mankind's needs. Reductions in land conversion to agriculture would reduce soil erosion, conserve carbon stores and sinks, and improve water quality. GM crops also could help limit environmental damage by reducing reliance on synthetic fertilizers and

---

Indur M. Goklany, who has a Ph.D. in electrical engineering from Michigan State University, is currently the D & D Foundation Julian Simon Fellow at the Political Economy Research Center (PERC) in Bozeman, Montana, while on leave from the United States Department of the Interior's Office of Policy Analysis. His work as an independent scholar at PERC is not part of his official duties with that department and does not necessarily reflect its views or policies or those of any other branch of the federal government.

pesticides, and increasing no-till cultivation, which would further reduce soil erosion, water pollution, and greenhouse gas emissions.

A comprehensive application of the precautionary principle indicates that a GM crop ban, contrary to the claims of its advocates, would *increase* overall risks to public health and to the environment. Thus it would be more prudent to research, develop, and commercialize GM crops than to ban such crops, provided reasonable caution is exercised.

Introduction

A popular formulation of the precautionary principle is contained in the Wingspread Declaration: "When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not established scientifically."[1]

In this study, I attempt to apply this formulation of the principle to devise precautionary policies for one of the most contentious environmental issues facing the globe, namely, the issue of bioengineered crops. In this analysis, I will examine and apply the precautionary principle comprehensively to a broader set of public health and environmental consequences of banning GM crops.

A Framework for Applying the Precautionary Principle Under Competing Uncertainties

Few actions are either unmitigated disasters or generate unadulterated benefits, and certainty in science is the exception rather than the rule. How, then, do we formulate precautionary policies in situations where an action could simultaneously lead to uncertain benefits and uncertain harms? Before applying the precautionary principle, it is necessary to formulate hierarchical criteria on how to rank various threats based upon their characteristics and the degree of certainty attached to them. Consequently, I offer six criteria to construct a precautionary "framework."

The first of these criteria is the *public health criterion*. Threats to human health should take precedence over threats to the environment. In particular, the threat of death to any human being outweighs similar threats to members of other species.

However, in instances where an action under consideration results in both potential benefits and potential costs to public health, additional criteria have to be brought into play. These additional criteria are also valid for cases where the action under consideration results in positive as well as negative environmental impacts unrelated to public health. I identify five such criteria as follows:

- The *immediacy criterion*. All else being equal, more-immediate threats should be given priority over threats that could occur later. Support for this criterion can be found in the fact that people tend to partially discount the value of human lives that might be lost in the more distant future.[2] While some may question whether such discounting may be ethical, it may be justified on the grounds that if death does not come immediately, with greater knowledge and technology, methods may be found in the future to deal with conditions that would otherwise be fatal which, in turn, may postpone death even longer. For instance, if an HIV-positive person in the United States did not succumb to AIDS in 1995, because of the advances in medicine there is a greater likelihood in 2000 that he would live out his "normal" life span. Thus, it would be reasonable to give greater weight to premature deaths that occur sooner. This is related to, but distinct from, the *adaptation criterion* noted below.

- The *uncertainty criterion*. Threats of harm that are more certain (have higher probabilities of occurrence) should take precedence over those that are less certain if otherwise their consequences would be equivalent. (I will, in this study, be silent on how equivalency should be determined for different kinds of threats.)

- The *expectation value criterion*. For threats that are equally certain, precedence should be given to those that have a higher expectation value. An action resulting in fewer expected deaths is preferred over one that would result in a larger number of expected deaths (assuming that the "quality of lives saved" are equivalent). Similarly, if an action poses a greater risk to biodiversity than inaction, the latter ought to be favored.

- The *adaptation criterion*. If technologies are available to cope with, or adapt to, the adverse consequences of an impact, then that impact can be discounted to the extent that the threat can be nullified.

- The *irreversibility criterion*. Greater priority should be given to outcomes that are irreversible, or likely to be more persistent.

In the following pages, I first will outline the potential benefits and costs to public health and the environment from research and development and commercialization of GM crops. I will then apply the relevant criteria to determine the appropriate policy pursuant to a comprehensive precautionary principle.

Potential Benefits of Bioengineered Crops

Environmental Benefits

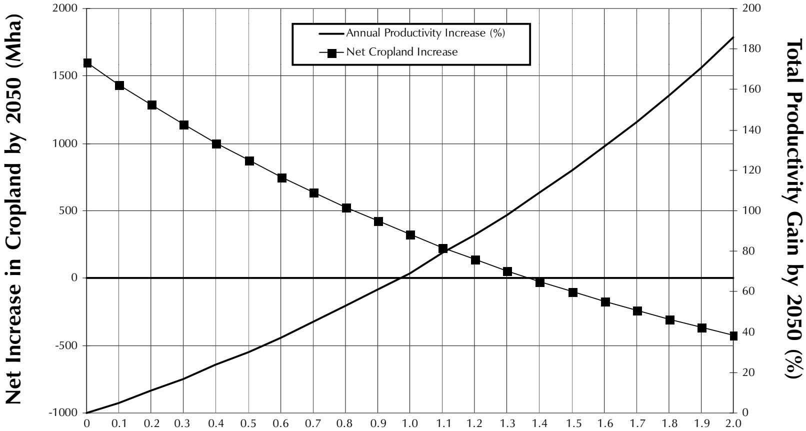
Agriculture and forestry, in that order, are the human activities that have the greatest effect on the world's biological diversity.[3] Today, agriculture uses account for 37 percent of global land area,[4] 70 percent of water withdrawals, and 87 percent of consumptive use worldwide.[5] It is also the major determinant of land clearance and habitat loss worldwide. Between 1980 and 1995, developing countries lost 190 million hectares (Mha) of forest cover mainly because their increase in agricultural productivity was exceeded by growth in food demand. Developed countries increased their forest cover by 20 Mha because their productivity outpaced demand. Agriculture and, to a lesser extent, forestry also affect biodiversity through water pollution and atmospheric transport due to such things as release of excess nutrients, pesticides, and silt.[6]

The predominant future environmental and natural resource problem for the globe is likely to be the challenge of meeting the human demand for food, nutrition, fiber, timber, and other natural resources while maintaining, if not improving, biological diversity. The question is whether biotechnology is more likely to help or to hinder reconciling these often opposing goals.

Demand for agricultural and forest products will almost certainly increase substantially. The world's population is expected to grow from about 6 billion today to between 10 and 11 billion in 2100, an increase of 70 to 80 percent. The average person is also likely to be richer, which ought to increase agricultural demand per capita. Accordingly, the predominant future environmental and natural resource problem for the globe is likely to be the challenge of meeting the human demand for food, nutrition, fiber, timber, and other natural resources while maintaining, if not improving, biological diversity.[7]

Figure 1

Net Habitat Loss to Cropland vs. Increase in Agricultural Productivity, 1997 to 2050



Source: Food and Agriculture Organization, FAO Databases, <*apps.fao.org*> (12 January 2000) per Indur M. Goklany, "Saving Habitat and Conserving Biodiversity on a Crowded Planet," *BioScience* 48 (November 1998): 941-53 and "Meeting Global Food Needs: The Environmental Trade-offs Between Increasing Land Conversion and Land Productivity," in *Fearing Food: Risk, Health and Environment*, ed. Julian Morris and Roger Bate (Oxford, England: Butterworth-Heinemann, 1999).

The question is whether biotechnology is more likely to help or to hinder reconciling these often opposing goals.[8] Although most of the following discussion focuses on agriculture, with particular emphasis on developing countries, much of it is equally valid for other human activities that use land and water, e.g., forestry, and in developed countries as well.

Decrease in Land and Water Diverted to Human Uses. The United Nation's latest most likely estimate is that global population, which hit 6 billion in 1999, will grow to 8.9 billion in 2050.[9] Figure 1, based on the methodology outlined by Goklany,[10] provides estimates of the additional land that would need to be converted to cropland from 1997 to 2050, as a function of the annual increase in productivity in the food and agricultural sector per unit of land. This figure assumes that global crop production per capita will grow at the same rate between 1997 and 2050 as it did between 1961-63 and 1996-98, and that new cropland will, on average, be as productive as existing cropland in 1997 (an optimistic assumption).

If the average productivity in 2050 is the same as it was in 1997—hardly a foregone conclusion[11]—the entire increase in production (106 percent under the above assumptions of growth in population and food demand) would have to come from an expansion in cropland. This would translate into additional habitat loss of at least 1,600 million hectares (Mha) (see Figure 1) beyond the 1,510 Mha devoted to cropland in 1997.[12] Much of that expansion would necessarily have to come at the expense of forested areas.[13] It would lead to massive habitat loss and fragmentation, and put severe pressure on the world's remaining biodiversity.

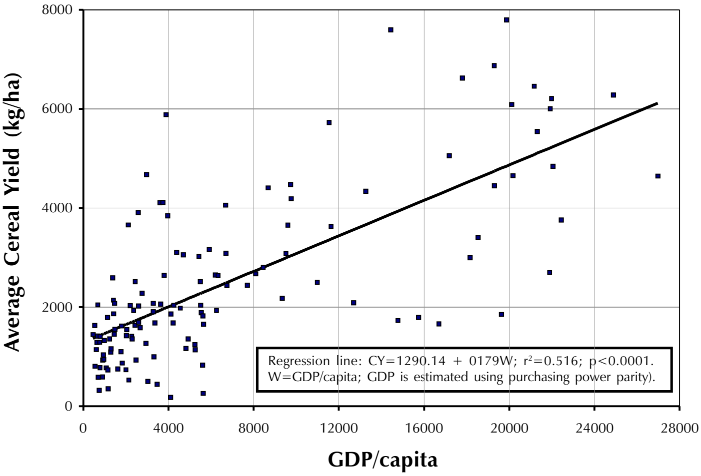
Productivity improvements could come much more rapidly and more surely if biotechnology is used. Biotechnology could more easily reduce current gaps between average yields and yield ceilings, and between yield ceilings and the theoretical maximum yield, as well as push up the theoretical maximum yield.

On the other hand, a productivity increase of 1.0 percent per year, equivalent to a cumulative 69 percent increase from 1997 to 2050, would reduce the amount of new cropland needed to meet future demand to 325 Mha. Such an increase in productivity is theoretically possible without resorting to biotechnology. It would require large investments in human capital, research and development, extension services, infrastructure expansion (to bring new lands, where needed, into production and integrate them with the rest of the world's agriculture system), inputs such as fertilizers and pesticides, and acquisition and operation of technologies to limit or mitigate environmental impacts of agriculture.[14]

A 1.0 percent a year increase in the net productivity of the food and agricultural sector (per unit area) is within the bounds of historical experience given that it increased 2.0 percent a year between 1961-63 and 1996-98.[15] More importantly, there are numerous existing but underused opportunities to enhance productivity in an environmentally sound manner. They are underused largely due to insufficient wealth—one reason why cereal yields are usually lower in poorer nations (see Figure 2). Merely increasing the 1996-98 average cereal yields in developing and transitional nations to the level attained by Belgium-Luxembourg (the

Figure 2

Cereal Yields as a Function of National per Capita Gross Domestic Product (GDP), 1995



Source: Goklany, *The Future of the Industrial System*, International Conference on Industrial Ecology and Sustainability, University of Technology of Troyes, Troyes, France, 22-25 September 1999.

country grouping that had the highest average yield, i.e. the yield ceiling, YC) would have increased global production in these years by 141 percent,[16] while increasing the average global cereal yield (2.96 tons per hectare [T/ha] in 1996-98)[17] to YC (7.80 T/ha in 1996-98) would increase global cereal production by 163 percent. Notably, the theoretical maximum yield is 13.4 T/ha or 350 percent greater than the average global cereal yield in 1996-98.[18]

Several conventional (i.e., non-bioengineering) methods could be used to increase net productivity in the food and agricultural sector from farm to mouth. These methods include: (1) further limiting pre-harvest crop losses to pests and diseases, which currently reduce global yields by an estimated 42 percent;[19] (2) increasing fertilizer use; (3) liming acidic soils; (4) adapting high yielding varieties to specific locations around the world (many scientists believe, however, that opportunities to further increase yields through conventional breeding techniques are almost tapped out);[20] and (5) reducing post-harvest and end-use losses,[21] which are estimated at about 47 percent worldwide.[22] Improvements in yields based upon conventional technologies will depend, in large part, on the ability of developing nations to afford and operate (through economic development and growth of human capital) the necessary technologies.

Productivity improvements could come much more rapidly and more surely if biotechnology is used. Biotechnology could more easily reduce current gaps between average yields and yield ceilings, and between yield ceilings and the theoretical maximum yield, as well as push up the theoretical maximum yield. This begs the question of whether environmental costs of such productivity increases will also increase and whether yield increases are sustainable in the long run. This issue will be discussed in greater detail later.

If through biotechnology the annual rate at which productivity can be increased sustainably rises from 1.0 percent a year to 1.5 percent a year, then cropland could actually be *reduced* by 98 Mha rather than increased by 325 Mha, relative to 1997 levels (see Figure 1). At the same time, the increased food demand of a larger and richer population could be met. If productivity could be doubled to 2.0 percent a year, then 422 Mha of current cropland could be returned to the rest of nature or made available for other human uses. Boosting annual productivity from 1 percent per year to 1.5 percent per year implies a net improvement in agricultural productivity of 30 percent due to biotechnology alone, while a 2 percent per year productivity increase corresponds to an overall improvement of 69 percent.

Several biotechnological crops, currently in various stages between research and commercialization, could put more food on the table per unit of land and water used in agriculture. Such crops, which could be particularly useful in developing nations, include:[23]

- *Cereals that are tolerant of poor climate and soil conditions.* Specifically, cereals that are tolerant to aluminum (so they can grow in acidic soils), drought, high salinity levels, submergence, chilling, and freezing are being developed.[24] The ability to grow crops in such conditions could be critical for developing countries. Forty-three percent of tropical soils are acidic.[25] More cropland is lost to high salinity than is gained through forest clearance. Salinity has rendered one-third of the world's irrigated land unsuitable for growing crops.[26] Moreover, if the world warms, the ability to tolerate droughts, high salinity, submergence, and acidity could be especially important for achieving global food security. In Kasuga et al.'s experiments,[27] 96 percent of genetically modified (GM) plants survived freezing, compared to less than 10 percent for the wild-type plant. Corresponding numbers for drought were 77 percent vs. 2 percent and, for salinity stress, 79 percent vs. 18 percent.

- *Rice that combines the best traits of the African and Asian varieties*. This bioengineered rice combines the ability of African rice to shade out weeds when young (which, however, inhibits photosynthesis later in the "pure" African variety) with the high yield capacity of the Asian variety.[28] In addition, the GM variety is highly resistant to drought, pests and diseases. This could be particularly useful for Africa because its increases in rice yields have so far lagged behind the rest of the world's. This lag is one reason why malnourishment in sub-Saharan Africa has increased in the past several decades, in contrast to improved trends in nutrition elsewhere.[29]

- *Rice with the property of being able to close stomata more readily*.[30] Rice with this characteristic ought to increase water use efficiency and net photosynthetic efficiency. Both aspects will be useful under dry conditions—conditions that, moreover, may get more prevalent in some areas if global warming continues.

- *Rice with the alternative C4 pathway for photosynthesis*. This trait could be especially useful if there is significant warming because the C4 pathway is more efficient at higher temperatures.[31] In addition, efforts are underway to try to reengineer RuBisCO—an enzyme critical to all photosynthesis—by using RuBisCO from red algae, which is a far more efficient catalyst for photosynthesis than that found in crops.[32]

- *Maize, rice, and sorghum with resistance to Striga, a parasitic weed that could decimate yields in sub-Saharan Africa*.[33]

- *Rice with the ability to fix nitrogen*.[34]

- *Rice and maize with enhanced uptakes of phosphorus and nitrogen*. Rice and maize production together account for 20 percent of global cropland use.[35]

- *Rice, maize, potato, sweet potato, and papaya with resistance to insects, nematodes, bacteria, viruses, and fungi.* For instance, papaya, which had been ravaged in Hawaii by the papaya ringspot virus, has now made a comeback due to a bioengineered variety resistant to that virus.[36]

- *Cassava, a staple in much of Africa, with resistance to the cassava mosaic virus and including a gene with an enzyme (replicase) with the ability to disrupt the life cycles of a number* *of other viruses*. This bioengineered cassava could, it is claimed, increase yields tenfold.[37] Also, because cassava naturally contains substances that can be converted to cyanide, it has to be carefully prepared before consumption. Work is proceeding on a genetically modified cassava that would be less toxic.[38]

- *Spoilage-prone fruits bioengineered for delayed ripening, thereby increasing their shelf life and reducing post-harvest losses*. These fruits include bananas and plantains (important sources of food for many African nations),[39] and melons, strawberries, and raspberries.[40]
- *Crops bioengineered to reduce the likelihood of their seed pods shattering*. Shattering seed pods reduce yields of crops such as wheat, rice, and canola. It is estimated that genetically modifying canola in this way could increase canola yields by 25 to 100 percent.[41]
- *High-lysine maize and soybeans, maize with high oil and energy content, and forage crops with lower lignin content*. These alterations ought to improve livestock feed and reduce the overall demand for land needed for livestock.[42]

If the methods and genes used to bioengineer the above crops can be successfully adapted and transferred to other vegetables, tubers, fruits, and even trees, that would help reduce future land and water needs for feeding, clothing, and sheltering humanity.

Reduction in the Release of Nutrients, Pesticides, Silt, and Carbon into the Environment. The above GM crops, by increasing crop yields and reducing the amount of cultivated land necessary, would also reduce the area subject to soil erosion from agricultural practices. Reducing soil erosion, in turn, would limit associated environmental effects on water bodies and aquatic species and would reduce loss of carbon sinks and stores into the atmosphere. Furthermore, many of the same GM crops could also directly reduce the amount of nutrients and pesticides released into the environment.[43] These bioengineered crops include:

- *Nitrogen-fixing rice, and rice and maize bioengineered with the ability to increase uptakes of phosphorus and nitrogen from the soil*. In Europe and the United States, only 18 percent of the nitrogen and 30 percent of the phosphorus in fertilizers are incorporated into crops. Between 10 and 80 percent of the nitrogen and 15 percent of the phosphorus end up in aquatic ecosystems. Much of the remainder accumulates in the soil, to be eroded later into aquatic systems.[44] These nitrogen-fixing crops would reduce reliance on fertilizers. As a result, they would reduce ground and surface water pollution, risks of chemical spills, and atmospheric emissions of nitrous oxide. Nitrous oxide is a greenhouse gas that, pound for pound over a 100-year period, is 310 times more potent a greenhouse gas than is carbon dioxide.[45]

- *Crops resistant to viruses, weeds, and other pests.* Striga-resistant maize, rice, and sorghum are examples. Various *Bt* crops, which contain genes from the *Bacillus thuringiensis* bacterium that has been used as a spray insecticide for four decades, also are being developed. One evaluation of *Bt* cotton in the United States estimates its planting on 2.3 million acres in 1998 reduced chemical pesticide use by over a million pounds, increased yields by 85 million pounds and netted farmers an added $92 million compared to the performance of conventional cotton seed.[46] The usage of *Bt* maize that was planted on 14 million acres in the United States reduced pesticide spraying on 2 million of those acres. The reduction in pesticide use would have been greater but for the fact that many farmers do not normally spray for the European maize borer, the target of the *Bt* toxin.[47]

  Developing countries also can reduce pesticide usage by using pest-resistant crops. India is the world's third largest producer of cotton. The crop is grown on only 5 percent of India's land, yet cotton farmers buy about 50 percent of all pesticides used in the country.[48] In 1998, the devastation caused by pests reportedly contributed to 500 suicides among Indian cotton farmers whose crops had failed. Field trials of *Bt* cotton at 30 locations in India show a 14 to 38 percent yield increase despite suspension of any spraying.[49]

- *Low phytic acid corn and soybean and phytase feed.* These altered crops help livestock better digest and absorb phosphorus. As a result, they can reduce phosphorus in animal waste and decrease runoff into streams, lakes, and other water bodies, mitigating one of the major sources of excess nutrients in the environment.[50] These GM crops would also reduce the need for inorganic phosphorus supplements in feed.

- *Crops tolerant of various herbicides, so that those herbicides can be used to kill weeds, but not the crop itself.* Herbicide-tolerant crops are among the most common applications of biotechnology today. One commercially available example is "Roundup Ready" soybeans, which are engineered to be tolerant to glyphosate. There are several potential benefits associated with such crops. They could help reduce the amount, toxicity, and persistence of herbicides employed. So far results from the field are mixed. Planting these crops seems to have reduced application of more hazardous and longer-lasting herbicides (e.g., acetochlor), although overall herbicide use may have increased.[51]

  Such herbicide-tolerant crops also would increase yields, while facilitating no-till cultivation. No-till cultivation is a highly effective method of stemming soil erosion and, thus, preserves future agricultural productivity. Erosion from cultivated land can be particularly damaging to the environment because the eroded particles can transport fertilizers and pesticides into aquatic systems and into the atmosphere. Finally, as noted, soil erosion releases stored carbon into the atmosphere.

Other Environmental Benefits of Bioengineered Plants and Trees. Crops can also be engineered to directly clean up environmental problems. For instance, GM plants can be used for bioremediation. Crops can be engineered to selectively absorb various metals and metal complexes such as aluminum, copper, and cadmium from contaminated soils.[52] Such plants could, for instance, detoxify methyl mercury in soils, thereby removing it from the food chain.

Researchers have also genetically modified aspen trees to produce 50 percent less lignin and 15 percent more cellulose. Lignin, a component of all wood, must be chemically separated from cellulose to make the pulp used in paper production. The GM tree has half the normal lignin to cellulose ratio of 1 to 2. Overall, 15 percent more pulp may be produced from the same amount of wood. Moreover, the GM trees are 25 to 30 percent taller. Thus, the land, chemicals, and energy used to make a given quantity of paper ought to be reduced substantially and result in significantly lower environmental impacts at every stage, from tree farming to paper production.[53]

Other potential applications of biotechnology that could reduce environmental impacts include production of biodegradable plastics using oilseed rape and production of colored cotton, which could reduce reliance on synthetic dyes.[54]

Public Health Benefits

Having sufficient quantities of food is often the first step to a healthy society.[55] The increase in food supplies per capita during the last half-century is a major reason for the worldwide improvement in health status during that period. Between 1961 and 1997, food supplies per capita increased 23 percent.[56] Thus, despite a 40 percent increase in population between 1969-71 and 1994-96, chronic undernourishment in developing countries dropped from 35 to 19 percent of their population.[57] Improved nourishment helped lower global infant mortality rates from 156 per 1,000 live births to 57 per 1,000 live births between 1950-55 and 1998. Life expectancies increased from 46.5 years to 65.7 years between 1950-55 and 1997. Better nourishment also enabled the average person to live a more fulfilling and productive life.[58]

Having sufficient quantities of food is often the first step to a healthy society. The increase in food supplies per capita during the last half-century is a major reason for the worldwide improvement in health status during that period.

Despite unprecedented progress during the last century, billions of people still suffer from undernourishment, malnutrition, and other ailments due, in whole or part, to insufficient food or poor nutrition. Table 1 lists the current extent and consequences of some of these food- and nutrition-related problems, and a qualitative assessment of the likelihood that using GM, rather than conventional, crops could reduce their numbers.

As shown in Table 1, about 825 million people currently are undernourished, i.e. cannot meet their basic needs for energy and protein.[59] Reducing these numbers over the next half-century while also reducing pressures on biodiversity in the face of anticipated population increases of 1.3 to 4.7 billion[60] requires increasing the quantity of food produced per unit of land and water. As discussed above, GM crops could help in this struggle.

Increasing food quantity is not enough; improving the nutritional quality of food is just as important. The diets of nearly half the world's population are deficient in iron, vitamin A, or other micronutrients (see Table 1). Such deficiencies can lead to disease and premature death.[61] About 2 billion people do not have enough iron in their diets, making them susceptible to anemia. Another 260 million suffer from subclinical levels of vitamin A deficiency, which causes clinical xerophthalmia which, if untreated, may lead to blindness, especially in children. Vitamin A is also crucial for effective functioning of the immune system.[62] Through the cumulative effects of these deficiencies, in 1995, malnutrition was responsible for 6.6 million or 54 percent of the deaths worldwide in children under five years of age. These nutritional shortfalls also resulted in stunting in 200 million children, and clinical xerophthalmia in about 2.7 million people.[63]

In addition to helping to ensure that adequate quantities of food are available, bioengineering could also help reduce many of these micronutrient deficiencies. For instance, Swiss scientists have developed "golden rice" that is rich in beta-carotene, a precursor to vitamin A, and have crossed it with another bioengineered strain rich in iron and cysteine, which allows iron to be absorbed in the digestive tract. Two-thirds of a pound of this rice, an average daily ration in the tropics, will provide the average daily vitamin A requirement while reducing iron deficiency. An ancillary benefit is that golden rice would reduce the need for meat—one of the primary sources for dietary iron. As a result, overall demand for livestock feed, and the land, water, and other inputs necessary to produce that feed could be reduced to some degree.[64]

Scientists are also working on using bananas and other fruits as vehicles to deliver vaccines against the Norwalk virus, *E. coli*, hepatitis B, and cholera.[65] This could eventually lead to low-cost, efficient immunization of whole populations against common diseases with broader coverage than likely with conventional needle delivery.

Bioengineered crops can also help battle the so-called "diseases of affluence," namely, ischemic heart disease, hypertension, and cancer. According to the World Health Organization, these diseases accounted for 4.8 million or 60 percent of the total deaths in high-income countries, and 14.9 million or 32 percent of deaths in the low- and middle-income countries in 1998 (see Table 1).[66]

Several GM crops can help reduce this toll. For instance, genetically enhanced soybeans that are lower in saturated fats are already on the market. The International Food Information

Table 1

Current Extent of Public Health Problems Partly or Wholly Caused by Insufficient Food or Poor Nutrition, and the Likelihood That They Could Be Alleviated Using GM, Rather Than Conventional, Crops

Problem	**Current Extent (Year)**	**Likelihood that GM crops would reduce problem**
Undernourishment	825 million people (1994-96)	Very high
Malnutrition	6.6 million deaths per year in children under 5 years old (1995)	Very high
Stunting	200 million people (1995)	High
Iron-deficiency anemia	2,000 million people (1995)	High
Vitamin A deficiency	260 million people (1995)	High
Ischemic and cerebrovascular diseases	2.8 million deaths per year in high-income countries (1998) 9.7 million deaths per year in low/mid-income countries (1998) (includes those due to smoking)	Moderate
Cancers	2.0 million deaths per year in high-income countries (1998) 5.2 million deaths per year in low/mid-income countries (1998) (includes those due to smoking)	Moderate

Sources: World Health Organization, *The World Health Report 1999* (Geneva: World Health Organization, 1999); Food and Agriculture Organization, FAO Databases, at *apps.fao.org*; id., “The State of Food Insecurity in the World,” at *www.fao.org/FOCUS/E/SOFI/home-e.htm*, 1999.

Council also notes that biotechnology could make soybean, canola, and other oils and their products, such as margarine and shortenings, more healthful.[67] Bioengineering could produce peanuts with improved protein balance, tomatoes with increased antioxidant content, potatoes with higher starch than conventional potatoes (reducing the amount of oil absorbed in French fries and potato chips), fruits and vegetables fortified with (or containing higher levels of) vitamins such as C and E, and higher-protein rice, using genes transferred from pea plants.

In addition to helping to ensure that adequate quantities of food are available, bioengineering could also help reduce many micronutrient deficiencies.

Moreover, levels of mycotoxins, which apparently increase with insect damage in crops, are lower on *Bt* corn. Some mycotoxins, such as fumonisin, can be fatal to horses and pigs, and may be human carcinogens. Thus, *Bt* corn, whether used as food for humans or feed for livestock, may be a healthier product than conventional corn.[68]

GM plants may also be able to save life and limb. It may sound like science fiction, but there is some speculation that plants can be engineered to biodegrade explosives in land mines and in ordnance at abandoned munitions sites.[69]

Finally, to the extent pest-resistant GM plants can reduce the amount, toxicity, and/or persistence of pesticides used in agriculture, accidental poisonings and other untoward health effects on farm workers or their immediate families could be reduced.

Potential Costs of Bioengineered Crops

Adverse Environmental Consequences

The major environmental concerns regarding GM crops are those related to crops that are designed to be resistant to pests and tolerant of herbicides. One potential risk is that target pests will become resistant to toxins produced by pest-resistant GM crops, such as *Bt* corn or *Bt* cotton. Although this is a possibility even if *Bt* is delivered via conventional sprays on non-GM plants, it is of greater concern with *Bt* plants. Under conventional spraying, target pests are exposed to *Bt* toxins only for brief periods, whereas currently available *Bt* crops produce toxins throughout the growing season. Thus, genetically engineered *Bt* crops could increase the chances of developing *Bt*-resistant pests.[70] Some laboratory studies suggest that target pests may evolve resistance more rapidly than previously thought possible.[71]

Strategies used to address pest resistance due to conventional pesticide spraying can, and should, be adapted for GM crops. Such strategies include ensuring that plants deliver high doses of *Bt*, while simultaneously maintaining refuges for non-*Bt* crops to ensure pest populations remain susceptible to *Bt*. EPA has established the requirement that *Bt* corn farmers plant 20 percent of their land in non-*Bt* corn as refuges. For *Bt* corn grown in cotton areas, farmers must plant at least 50 percent non-*Bt* corn. In addition, EPA requires expanded monitoring to detect any potential resistance.[72] Other strategies to delay development of pesticide resistance include crop rotation,[73] developing crops with more than one toxin gene acting on separate molecular targets,[74] and inserting the bioengineered gene into the chloroplast since that ought to express *Bt* toxin at higher levels.[75] Clearly, farmers have an economic stake in implementing such adaptive strategies so that their crop losses to pests are kept in check in the long term as well as the short term.

Another source of risk is that *Bt* from pest resistant plants could harm, if not kill, non-target species. This could happen if, for instance, *Bt*-laden pollen were to drift away from the field or if the toxin were to leak through the roots and be consumed by non-target organisms.[76] Losey, Rayor, and Carter showed in a laboratory study that the mortality rate of Monarch butterfly larvae fed for four days with milkweed dusted with *Bt* maize pollen was 44 percent, compared to zero for the control case, which used milkweed dusted with ordinary pollen.[77]

The extent to which, or even whether, the Monarch butterfly population would be affected in the real world is a matter of debate.[78] One study suggests that under a worst-case scenario as much as 7 percent of the North American Monarch population (estimated at 100 million) may die, although the real-world effect would probably be smaller.[79] Some have also argued that the major threat to Monarchs is the habitat loss in their wintering grounds in Mexico.[80] Perhaps more importantly, the inadvertent effects of *Bt* crops due to pollen dispersal or root leakage could be virtually eliminated by bioengineering genes into the chloroplast rather than into nuclear DNA.[81]

Bt could also enter the food chain through root leakage or if predators prey on target pests. For instance, studies have shown that green lacewing larvae, a beneficial insect, that ate maize borers fed with *Bt* maize were more likely to die.[82] Again, the real world significance of this experimental finding has been disputed based on the long history of *Bt* spraying on crops and other studies that showed beneficial insects essentially unharmed by such spraying.[83]

There is also a concern that bioengineered genes from herbicide- or pest-tolerant crops might escape into wild relatives leading to "genetic pollution" and creating "superweeds." Such a development would have an adverse economic impact on farmers, reducing crop yields and detracting from the very justification for using such GM crops.[84] Clearly, farmers have a substantial incentive for preventing weeds from acquiring herbicide tolerance and, if that fails, to keep such weeds in check.

Gene escape is possible if sexually compatible wild relatives are found near fields planted with GM crops. This is a possibility in the United States for sorghum, oats, rice, canola, sugar beets, carrots, alfalfa, sunflowers, and radishes.[85] However, the most common GM crops, namely soybeans and corn, have no wild U.S. relatives.[86] Moreover, centuries of conventional breeding have rendered a number of important crops, e.g., maize and wheat, "ecologically incompetent" in many areas,[87] although that is no guarantee of safety.[88] Despite the use of conventionally-bred herbicide-tolerant plants, there has been no upsurge in problems due to herbicide-tolerant weeds.[89] If any weeds develop such tolerance, available crop management techniques (such as another herbicide) can be used to control them.

Gene escape from GM crops to wild relatives is also an environmental concern. It has been argued that herbicide-tolerant "superweeds" could invade natural ecosystems. It is unclear why such a weed would have a competitive advantage in a natural system unless that system is treated with the herbicide in question. But if it is so treated, does it still qualify as a natural system? Regarding ecosystem function and biodiversity, the significance of genetic pollution, per se, is unclear. Would gene escape affect ecosystem function negatively? Does gene escape diminish or expand biodiversity?[90]

Genes also may escape from GM crops to non-GM crops of the same species. Such an escape would be unpopular with organic farmers, who are afraid it might "adulterate" their produce. Of course, producers of GM seeds and farmers planting GM seeds are not eager to have someone else profit from their investments either. The chances of such gene escape can be reduced by maintaining a buffer between the two crops. The Royal Society also notes that because more crops (including corn, sorghum, sugar beets, and sunflowers) are now grown from hybrid seeds, this provides a measure of built-in security against such gene transfers.[91]

Gene escape could be limited further if the GM plant was engineered to be sterile or prevented from germinating using, for instance, "terminator technology." An alternative approach would be to insert the gene into the chloroplast, which would preclude its spread through pollen or fruit, as well as prevent root leakage.[92]

Finally, there is a concern that in the quest to expand yields, GM plants will work too well in eliminating pests and weeds, leading to a further simplification of agricultural ecosystems and further decreasing biodiversity. This concern, in conjunction with the other noted environmental concerns, needs to be weighed against the cumulative biodiversity benefits of reduced conversion of habitat to cropland, and decreased use of chemical inputs.

Adverse Public Health Consequences

A major health concern is that the new genes inserted into GM plants could be incorporated into a consumer's genetic makeup. However, there is no evidence that any genes have ever been transferred to human beings through food or drink despite the fact that plant and animal DNA has always been a part of the daily human diet.[93] In fact, an estimated 4 percent of the human diet is composed of DNA,[94] and an average adult Briton consumes 150,000 kilometers of DNA in an average meal.[95] It is unclear, for instance, why consuming beans which have been modified with genes from a pig would pose a greater risk to public health than consuming a dish of non-GM pork and beans.

Another concern is that genes transferred from foods to which many people are allergic could trigger allergies in unsuspecting consumers of such GM crops. Between 1 and 3 percent of adults and 5 and 8 percent of children in the United States suffer from food allergies. Each year, food allergies cause 135 fatalities and 2,500 emergency room visits.[96]

This concern regarding allergic reactions to GM foods can be traced to pre-commercialization tests of a GM soybean conducted by Pioneer Hi-Bred. The tests showed that a soybean that had been bioengineered to boost its nutritional quality using a gene from the Brazil nut was, in fact, allergenic.

Although this example shows that GM foods can be tested prior to commercialization for their allergic potential, opponents of GM foods have used this as an argument against bioengineered crops. Several databases of known allergens could be used to help identify problematic GM products before they are developed.[97] In fact, because bioengineering allows more precise manipulation of genes than does conventional plant breeding, it could be used to render allergenic crops non-allergenic.[98]

Yet another potential negative effect on public health is that antibiotic-resistant "marker" genes that are used to identify whether a gene has been successfully incorporated into a plant could, through consumption of the antibiotic gene by humans, accelerate the trend toward antibiotic-resistant diseases. However, compared to the threat posed by the use of antibiotics in feed for livestock and their overuse as human medicines, the increased risk due to such markers is slight.[99]

Applying the Precautionary Principle

The above discussion indicates there are risks associated with either the use or the non-use of GM crops. Here I will apply the various criteria outlined in the framework presented previously for valuing actions that could result in uncertain costs and uncertain benefits. Ideally, each criterion should be applied individually to the human mortality, the non-mortality public health, and the non-public-health-related environmental consequences of GM crop use. However, because the severity and degree of uncertainty associated with the various costs and benefits for each of these sets of consequences are not equivalent, I will apply several criteria simultaneously.

Public Health Consequences

Population could increase 50 percent between 1998 and 2050 (from 5.9 billion to 8.9 billion, according to the United Nation's best estimate). Hence, by 2050, undernourishment, malnutrition, and their consequences on death and disease might also be expected to increase by 50 percent worldwide, if global food supply increases by a like amount and all else remains equal. Unless food production outstrips population growth significantly over the next half century, billions in the developing world may suffer annually from undernourishment, hundreds of millions may be stunted, and millions may die from malnutrition. Based on the sheer magnitude of people at risk, and the degree of certainty of the public health consequences, one can state with confidence that limiting GM crops will increase death and disease, particularly among the poor.

GM crops could also reduce or postpone deaths due to diseases of affluence. The probability of reducing these deaths by moving forward with GM crops is lower than that of reducing deaths due to hunger and malnutrition, of course. But the expected number of deaths postponed could run into the millions. For instance, a 10 percent decrease in the 15 million deaths due to cancer, ischemic, and cerebrovascular diseases in low- and middle-income nations translates to 1.5 million lives saved (see Table 1).

Unless food production outstrips population growth significantly over the next half century, billions in the developing world may suffer annually from undernourishment and millions may die from malnutrition. Based on the sheer magnitude of people at risk, and the degree of certainty of the public health consequences, one can state with confidence that limiting GM crops will increase death and disease, particularly among the poor.

By contrast, the negative public health consequences of ingesting GM foods are speculative (e.g., the effects due to ingesting transgenes) or relatively minor in magnitude (e.g., a potential increase in antibiotic resistance or increased incidence of allergic reactions). Moreover, it is possible to reduce, if not eliminate, the effects of even those minor impacts.

As noted previously, the likelihood of allergic reactions can be reduced by checking various databases of known allergens prior to developing a GM crop and by testing food from such crops prior to commercialization. With respect to the risk of increasing antibiotic resistance, Novartis has developed a sugar-based alternative to antibiotic-resistant marker genes that has been used to develop about a dozen GM crops, including maize, wheat, rice, sugar beet, oilseed rape, cotton, and sunflowers.[100] With additional research, marker genes may be devised for other crops. Alternatively, practical methods of removing or repressing antibiotic resistant marker genes may be developed.[101]

Thus, with respect to human mortality and morbidity, and employing the “uncertainty,” “expectation value,” and “adaptation” criteria outlined in the framework developed previously, the precautionary principle *requires* that we continue to research, develop, and commercialize (with appropriate safeguards, of course) those GM crops that would increase food production and generally improve nutrition and health, especially in the developing world.

Some have argued that many developed countries are "awash in surplus food."[102] Thus, goes this argument, developed countries have no need to boost food production. However, this argument ignores the fact that reducing those surpluses would be almost as harmful to public health in developing countries as curtailing their food production directly.

Even for developed countries, the potential public health benefits of GM crops far outweigh in magnitude and certainty the speculative health consequences of ingesting GM foods.

At present, net cereal imports of the developing countries exceed 10 percent of their production. Trade (and aid) voluntarily moves the surplus production in developed countries to developing countries suffering from food deficits. Without this movement of developed nations' food surpluses, food supplies in developing countries would be lower, food prices would be steeper, undernourishment and malnutrition would be higher, and associated health problems, such as illness and premature mortality, would be greater. As already noted, developing countries' food deficits are only expected to increase in the future because of high population growth rates and, possibly, could be further worsened by global warming. Therefore, developed countries' food surpluses will at least be as critical for future food security in developing countries as they are today.

The above argument against GM crops also assumes that such crops will produce little or no benefits for the inhabitants of developed countries. But, as noted, GM crops are also being engineered to improve nutrition in order to combat diseases of affluence afflicting populations in developed, as well as developing, nations. As noted, these diseases are among the major causes of premature death in the developed countries—approximately 4.8 million a year currently (see Table 1).[103] Similarly, the health benefits of a GM crop like "golden rice," for instance, do not have to be confined to developing countries; developed countries, too, could avail themselves of its benefits. Thus even for developed countries, the potential public health benefits of GM crops far outweigh in magnitude and certainty the speculative health consequences of ingesting GM foods.

Hence, the "expectation value" and "uncertainty" criteria applied to public health require developed countries to develop, support, and commercialize yield-increasing and health- and nutrition-enhancing GM crops in order to improve public health worldwide.

Environmental Consequences

Another, related argument against using GM foods to increase food production is that there is no shortage of food in the world today, that the problem of hunger and malnutrition is rooted in poor distribution and unequal access to food because of poverty. Therefore, the argument goes, it is unnecessary to increase food production; ergo, there is no compelling need for biotechnology.[104]

But even if everyone had equal access—an unlikely proposition, at best—finite levels of food, fiber, and timber would still have to be produced to meet the demand. A figure similar to Figure 1 could be developed for any level of food demand whether it is, say, half that of today (perhaps because of a perfect, cost-free distribution system and a magical equalization of income) or whether it is four times that (possibly due to runaway population growth). Thus, regardless of the level of demand, limiting GM crops would lower crop and forest yields per unit of land and water used. To compensate for the lower yields, more land and water would have to be pressed into humanity's service, leaving that much less for the rest of nature.[105]

Moreover, if bioengineering succeeds in improving the protein and micronutrient content of vegetables, fruits, and grains, it might persuade many more people to adopt and persevere with vegetarian diets, thereby reducing the additional demand that meat-eating places on land and water. Giving up GM crops would further increase pressures on biodiversity due to excess nutrients, pesticides, and soil erosion. Reduced conversion of habitat and forest to crop and timber land coupled with reduced soil erosion due to increased no-till cultivation of bioengineered crops also would help limit losses of carbon reservoirs and sinks (thereby potentially reducing global warming).

Arrayed against these benefits to ecosystems, biodiversity, and carbon stores and sinks from deploying GM crops are the environmental costs from widespread planting of pest-resistant and herbicide-tolerant GM crops *minus* the environmental costs of conventional farming practices. These costs include a potential decrease in the diversity of the flora and fauna associated with, or in the immediate vicinity of, GM crops if they reduce more non-target pests and weeds than conventional farming practices, and the possible consequences of gene escape to weeds and non-GM crops.

Hence, with respect to the environmental consequences, one must still conclude, based on the "uncertainty" and "expectation value" criteria, that the precautionary principle requires the cultivation of GM crops. On net, bioengineered crops should conserve the planet's habitat, biodiversity, and carbon stores and sinks, provided due caution is exercised, particularly with respect to herbicide-tolerant and pest-resistant GM crops.

The precautionary principle often has been invoked to justify a prohibition of GM crops. However, this policy is based upon a selective application of the precautionary principle to a limited set of consequences of such a policy.

It may be argued that if genes escape and are established in "natural" ecosystems, this may lead to irreversible harm to the environment; thus, under the "irreversibility" criterion, GM crops ought to be banned. However, increased habitat clearance and land conversion resulting from such a ban may be at least as irreversible, particularly if it leads to species extinctions.

It is worth noting that the precautionary principle supports using terminator-type technology because it would minimize the possibility of gene transfer to weeds and non-GM plants. Some of the same groups that profess environmental concerns about genetic pollution are the most vehement critics of terminator technology.[106] Clearly, in the policy calculus of these groups, the presumed negative economic consequences to farmers due to their inability to propagate GM crops from sterile seeds (and the antipathy of these organizations toward multinationals' profits) outweighs the environmental benefits of GM crops.

Conclusion

The precautionary principle often has been invoked to justify a prohibition of GM crops.[107] However, this policy is based upon a selective application of the precautionary principle to a limited set of consequences of such a policy. Specifically, the justification for a ban considers the potential public health and environmental benefits of a ban on GM crops, but ignores the probable public health and environmental benefits that would necessarily be foregone.

By comparison with conventional crops, GM crops would increase the quantity and nutritional quality of food supplies. Bioengineered crops hold the promise of improving public health and reducing mortality rates worldwide. In addition, cultivation of GM, rather than conventional, crops would be more protective of habitat, biological diversity, and carbon stores and sinks. Crops are being genetically modified to increase productivity, thus reducing the amount of land and water that would otherwise have to be diverted to humanity's needs. GM crops could also reduce the environmental damage resulting from the use of synthetic fertilizers and pesticides, and from soil erosion.

A ban on GM foods, contrary to the claims of its proponents, would be imprudent rather than precautionary. The precautionary principle—properly applied, using a broader consideration of the public health and environmental consequences of a ban—argues instead for a sustained effort to research, develop, and commercialize GM crops.

A ban on GM foods, contrary to the claims of its proponents, would be imprudent rather than precautionary. The precautionary principle—properly applied, using a broader consideration of the public health and environmental consequences of a ban—argues instead for a sustained effort to research, develop, and commercialize GM crops, provided reasonable caution is exercised during testing and commercialization of these crops.

In this context, an action, precondition, or restriction regarding testing or commercialization is "reasonable" if its public health benefits are not likely to be negated by reductions in the quantity or quality of food that would otherwise be available. Halting testing in this instance would increase food costs and reduce broader access to higher quality food, particularly for the poorer and most vulnerable segments of society. Also the environmental gains flowing from a "reasonable" precaution should more than offset the environmental gains that could otherwise be obtained. In other words, a reasonable precaution is one that does not kill the goose that lays the golden egg, as a ban on GM crops would do.

Endnotes

1. Carolyn Raffensperger, Joel Tickner, and Wes Jackson, eds., *Protecting Public Health and the Environment: Implementing the Precautionary Principle* (Washington, D.C.: Island Press, 1999).
2. Maureen L. Cropper and Paul R. Portney, "Discounting Human Lives," *Resource*, no. 108 (1992): 1-4.
3. Indur M. Goklany, "Saving Habitat and Conserving Biodiversity on a Crowded Planet," *BioScience* 48 (November 1998): 941-53.
4. Food and Agriculture Organization, FAO Databases, <*apps.fao.org*> (12 January 2000).
5. United Nations Commission on Sustainable Development, Fifth Session, Document E/CN.17/1997/9, <*gopher://gopher.un.org:70/00/esc/cn17/1997/off/97-9.EN*> (23 July 1999).
6. Wilcove, D. S. et al., "Quantifying Threats to Imperiled Species in the United States," *BioScience* 48 (August 1998): 607-15.
7. Indur M. Goklany, "Saving Habitat and Conserving Biodiversity on a Crowded Planet."; id., "The Importance of Climate Change Compared to Other Global Changes," in *Proceedings of the Second International Specialty Conference: Global Climate Change—Science, Policy, and Mitigation/Adaptation Strategies, Crystal City, Virginia, 13-16 October 1998* (Sewickley, Penn.: Air and Waste Management Association, 1998); id., "Meeting Global Food Needs: The Environmental Trade-offs Between Increasing Land Conversion and Land Productivity," in *Fearing Food: Risk, Health and Environment*, ed. Julian Morris and Roger Bate (Oxford, England: Butterworth-Heinemann, 1999); and id., "Potential Consequences of Increasing Atmospheric CO_2 Concentration Compared to Other Environmental Problems," *Technology* (2000, in press).
8. Goklany, "Meeting Global Food Needs."
9. United Nations Population Division, *Long-Range World Population Projections: Based on the 1998 Revision*, Report ESA/P/WP.153 (New York: United Nations, 1999).
10. Goklany, "Saving Habitat."; id., "Meeting Global Food Needs."
11. Goklany, "Saving Habitat."
12. Food and Agriculture Organization, FAO Databases.
13. Goklany, "Saving Habitat."
14. Goklany, "Meeting Global Food Needs."
15. Food and Agriculture Organization, FAO Databases.
16. Ibid.
17. Ibid.
18. Hans Linnemann et al., *MOIRA: Model of International Relations in Agriculture. Report of the Project Group "Food for a Doubling World Popu-*

lation" (Amsterdam: North Holland Publishing Co., 1979).

19. E.-C. Oerke et al., "Conclusion and Perspectives," in *Crop Production and Crop Protection: Estimated Losses in Major Food and Cash Crops*, ed. E.-C. Oerke et al. (Amsterdam: Elsevier Science, 1994).

20. Gordon Conway and Gary Toenniessen, "Feeding the World in the Twenty-First Century," *Nature* 402 (2 December 1999 supplement): C55-8; Charles C. Mann, "Crop Scientists Seek a New Revolution," *Science* 283 (15 January 1999): 310-14.

21. Indur M. Goklany and Merritt W. Sprague, *An Alternative Approach to Sustainable Development: Conserving Forests, Habitat and Biological Diversity by Increasing the Efficiency and Productivity of Land Utilization* (Washington, D.C.: Office of Program Analysis, Department of the Interior, 1991).

22. William H. Bender, "An End Use Analysis of Global Food Requirements," *Food Policy* 19, no. 4 (1994): 381-95.

23. Indur M. Goklany, "Biotechnology and Biodiversity: The Risks and Rewards of Genetically Modified Crops," (*BioScience*, 2000, in review).

24. Juan Manuel de la Fuente et al., "Aluminum Tolerance in Transgenic Plants by Alteration of Citrate Synthesis," *Science* 276 (6 June 1997): 1566-68; Maris P. Apse et al., "Salt Tolerance Conferred by Overexpression of a Vacuolar Na+/H+ Antiport in Arabidopsis," *Science* 285 (20 August 1999): 1256-58; Mie Kasuga et al., "Improving Plant Drought, Salt, and Freezing Tolerance by Gene Transfer of a Single Stress-inducible Transcription Factor," *Nature Biotechnology* 17 (March 1999): 287-91; M.S. Swaminathan, "Genetic Engineering and Food, Ecological and Livelihood Security in Predominantly Agricultural Developing Countries" (paper presented at the joint Consultative Group on International Agricultural Research/National Academy of Sciences Biotechnology Conference, Washington, D.C., October 1999), <*www.cgiar.org/biotechc/swami.htm*> (11 November 1999); Conway and Toenniessen, "Feeding the World in the Twenty-First Century."; Anne S. Moffat, "Crop Engineering Goes South," *Science* 285 (16 July 1999): 370-71; Qifa Zhang, "Meeting the Challenges of Food Production: The Opportunities of Agricultural Biotechnology in China" (paper presented at CGIAR/NAS Biotechnology Conference, Washington, D.C., October 1999), <*www.cgiar.org/biotechc/zhang.htm*> (11 November 1999); Elisabeth Pennisi, "Plant Biology: Transferred Gene Helps Plants Weather Cold Snaps," *Science* 280 (3 April 1998): 36; see also Kirsten Jaglo-Ottosen et al., "Arabidopsis CBF-1 Overexpression Induces COR Genes and Enhances Freezing Tolerance," *Science* 280 (3 April 1998): 104-6.

25. World Bank, *New & Noteworthy in Nutrition*, Issue 24 (13 October 1994), <*www.worldbank.org/html/extdr/hnp/nutrition/nnn/nnn24.htm*> (5 January 2000).

26. Wolf B. Frommer, Uwe Ludewig, and Doris Rentsch, "Taking Transgenic Plants with a Pinch of Salt," *Science* 285 (20 August 1999): 1222-23.

27. Kasuga et al., "Improving Plant Drought, Salt, and Freezing Tolerance."

28. Conway and Toenniessen, "Feeding the World in the Twenty-First Century."

29. Goklany, "Saving Habitat."

30. Mann, "Crop Scientists Seek a New Revolution."

31. Maurice S. B. Ku et al., "High-level Expression of Maize Phosphoenolpyruvate Carboxylase in Transgenic Plants," *Nature Biotechnology* 17 (January 1999): 76-80; Gerry Edwards, "Tuning up Crop Photosynthesis," *Nature Biotechnology* 17 (January 1999): 22-23; Conway and Toenniessen, "Feeding the World in the Twenty-First Century."

32. Charles C. Mann, "Genetic Engineers Aim to Soup Up Crop Photosynthesis," *Science* 283 (15 January 1999): 314-16.

33. Charles C. Mann, "Biotech Goes Wild," *Technology Review* (July/August 1999), <*www.techreview.com/articles/july99/full_text.htm*> (21 February 2000); Colin MacIlwain, "Access Issues May Determine Whether Agri-Biotech Will Help the World's Poor," *Nature* 402 (25 November 1999): 341-45; Conway and Toenniessen, "Feeding the World in the Twenty-First Century."

34. International Rice Research Institute, "Nitrogen-fixing Rice Moves Closer to Reality," IRRI Science Online, 21 December 1999, <*www.iclarm.org/irri/Science.html*> (1 February 2000).

35. Conway and Toenniessen, "Feeding the World in the Twenty-First Century."; C. S. Prakash, "A First Step Towards Engineering Improved Phosphate Uptake," *ISB News Report*, May 1998, <*http://www.isb.vt.edu/news/1998/news98.may.html#may9802*> (15 January 2000); *Inside Purdue*, "Raghothama: Phosphorus Uptake Gene Discovered," 13 January 1998, <*www.purdue.edu/PER/1.13.98.IP.html*> (19 January 2000).

36. Conway and Toenniessen, "Feeding the World in the Twenty-First Century."; Dan Ferber, "Risks and Benefits: GM Crops in the Cross Hairs," *Science* 286 (26 November 1999): 1662-66.

37. Anne S. Moffat, "Engineering Plants to Cope with Metals," *Science* 285 (16 July 1999): 369-70.

38. Conway and Toenniessen, "Feeding the World in the Twenty-First Century."

39. Ibid.

40. Peggy G. Lemaux, "Plant Growth Regulators and Biotechnology," (paper presented at the Western Plant Growth Regulator Society, Anaheim, California, January 1999), <*plantbio.berkeley.edu/~outreach/REGULATO.HTM*> (19 January 2000).

41. Sarah J. Liljegren et al., "*SHATTERPROOF* MADS-box Gene Control Seed Dispersal in *Arabidopsis*," *Nature* 404 (13 April 2000): 766-70.

42. Barbara Mazur, Enno Krebbers, and Scott Tingey, "Gene Discovery

and Product Development for Grain Quality Traits," *Science* 285 (16 July 1999): 372-75; Conway and Toenniessen, "Feeding the World in the Twenty-First Century."

43. Goklany, "Biotechnology and Biodiversity: Risks and Rewards."

44. Stephen Carpenter et al., "Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen," *Issues in Ecology* 3 (Summer 1998), <*esa.sdsc.edu/carpenter.htm*> (10 February 2000).

45. Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change*, ed. J. T. Houghton et al., (Cambridge, England: Cambridge University Press, 1996).

46. Ferber, "Risks and Benefits."

47. Ibid.

48. C. S. Prakash, "Relevance of Biotechnology to Indian Agriculture," May 1999, *www.teriin.org/discuss/biotech/abstracts.htm#relevance*> (15 January 2000).

49. The Hindu Business Line, "*Bt* Cotton Trials Show Yield Rise," 18 January 2000, <*www.indiaserver.com/bline/2000/01/19/stories/071903a1.htm*> (18 January 2000).

50. Grabau Laboratory, "Improving Phosphorus Utilization in Soybean Meal Through Phytase Gene Engineering," <*www.biotech.vt.edu/plants/grabau/projects.html*> (9 February 2000); Mikesell, Libby, "Ag Biotech May Help Save the Bay," Biotechnology Industry Organization, <*www.bio.org/food&ag/cbf.html*> (21 February 2000); CeresNet, "Environmental Benefits of Agricultural Biotechnology," 2 February 1999, <*www.ceresnet.org/Cnetart/990202_Environ_Benefits-AgBio.txt*> (10 February 2000).

51. Ferber, "Risks and Benefits."

52. Anne S. Moffat, "Engineering Plants to Cope with Metals."

53. Michigan Technological University, "New Aspen Could Revolutionize Pulp and Paper Industry," 11 October 1999, <*www.admin.mtu.edu/urel/breaking/1999/aspen.htm*> (10 January 2000).

54. Eleanor Lawrence, "Plastic Plants," *Nature Science Update* (24-30 September 1999) <*helix.nature.com/nsu/990930/990930-5.html*> (11 January 2000).

55. World Health Organization, *The World Health Report 1999* (Geneva: World Health Organization, 1999); Indur M. Goklany, "The Future of the Industrial System" (paper presented at the International Conference on Industrial Ecology and Sustainability, University of Technology of Troyes, Troyes, France, September 1999).

56. Food and Agriculture Organization, FAO Databases.

57. Food and Agriculture Organization, "The State of Food Insecurity in the World," <*www.fao.org/FOCUS/E/SOFI/home-e.htm*> (12 January 2000).

58. World Health Organization, *The World Health Report 1999*; United Nations Population Division, *Long-Range World Population Projections*; Goklany, "The Future of the Industrial System."

59. Food and Agriculture Organization, "The State of Food Insecurity in the World."

60. United Nations Population Division, *Long-Range World Population Projections*.

61. World Health Organization, *The World Health Report 1999*; Food and Agriculture Organization, "The State of Food Insecurity in the World."

62. World Health Organization, "About WHO: Nutrition," 21 September 1999, <*www.who.int/aboutwho/en/promoting/nutrition.htm*> (5 January 2000).

63. World Health Organization, "Malnutrition—The Global Picture," 2 November 1999, <*www.who.int/nut/malnutrition_worldwide.htm*> (5 January 2000).

64. Trisha Gura, "New Genes Boost Rice Nutrients," *Science* 285 (13 August 1999): 994-95; Mary Lou Guerinot, "The Green Revolution Strikes Gold," *Science* 287 (14 January 2000): 241-43; Xudong Ye et al., "Engineering the Provitamin A (Beta-Carotene) Biosynthetic Pathway into (Carotenoid-Free) Rice Endosperm," *Science* 287 (14 January 2000): 303-5; see also F. Goto et al., "Iron Fortification of Rice Seed by the Soybean Ferritin Gene," *Nature Biotechnology* 17 (March 1999): 282-86.

65. Anne S. Moffat, "Engineering Plants to Cope with Metals"; Paul Smaglik, "Needle-Free Vaccines: Success of Edible Vaccine May Depend on Picking Right Fruit," *The Scientist* 12 (17 August 1998), <*www.the-scientist.library.upenn.edu/yr1998/August/pg4_story2_980817.html*> (7 January 2000).

66. World Health Organization, *The World Health Report 1999*.

67. International Food Information Council, "*Backgrounder—Food Biotechnology*," updated April 1999, <*ificinfo.health.org/backgrnd/BKGR14.htm*> (12 January 2000).

68. Gary P. Munkvold and Richard L. Hellmich, "Genetically Modified, Insect Resistant Corn: Implications for Disease Management," APSnet Plant Pathology On-line feature, 15 October-30 November 1999 <*http://www.scisoc.org/feature/BtCorn/Top.html*> (19 February 2000).

69. Frederick Bolin, "Leveling Land Mines with Biotechnology," *Nature Biotechnology* 17 (August 1999): 732; Christopher E. French et al., "Biodegradation of Explosives by Transgenic Plants Expressing Pentaerythritol Tetranitrate Reductase," *Nature Biotechnology* 17 (May 1999): 491-94.

70. Fred Gould, "Sustaining the Efficacy of Bt Toxins," in *Agricultural Biotechnology and Environmental Quality: Gene Escape and Pest Resis-*

tance, ed. Ralph W. Hardy and Jane B. Segelken, NABC Report 10 (Ithaca, New York: National Agricultural Biotechnology Council, 1998); see also Theo Wallimann, "Bt Toxin: Assessing GM Strategies," *Science* 287 (7 January 2000): 41c.

71. Liu Yong-Biao et al., "Development Time and Resistance to *Bt* Crops," *Nature* 400 (5 August 1999): 519; AgBiotechNet, "Hot Topic: Bt Plants: Resistance and Other Issues: New Findings on Insect Resistance to Bt Cotton," July 1999, <www.agbiotechnet.com/topics/hot.asp> 4 February 2000.

72. Environmental Protection Agency, "*Bt* Corn Insect Resistance Management Announced for 2000 Growing Season," press release (14 January 2000).

73. Fred Gould, "Sustaining the Efficacy of Bt Toxins."

74. Gordon Conway, "Food for All in the Twenty-First Century," *Environment* 42 (January/February 2000): 8-18.

75. Henry Daniell, "The Next Generation of Genetically Engineered Crops for Herbicide and Insect Resistance: Containment of Gene Pollution and Resistant Insects," AgBiotechNet Vol.1 (August 1999), ABN 024, <*www.agbiotechnet.com/reviews/aug99/html/Daniell.htm*> (12 February 2000); Madhuri Kota et al., "Overexpression of the *Bacillus Thuringiensis* (*Bt*) CRy2Aa2 Protein in Chloroplasts Confers Resistance to Plants Against Susceptible and Bt-resistant Insects," in *Proceeding of the National Academy of Sciences* 96 (2 March 1999): 1840-45.

76. John E. Losey, Linda S. Rayor, and Maureen E. Carter, "Transgenic Pollen Harms Monarch Larvae," *Nature* 399 (20 May 1999): 214; Theo Wallimann, "Bt Toxin: Assessing GM Strategies."; Deepak Saxena, Saul Flores, and G. Stotzky, "Transgenic Plants: Insecticidal Toxin in Root Exudates from *Bt* Corn," *Nature* 402 (2 December 1999): 480.

77. Losey, Rayor, and Carter, "Transgenic Pollen Harms Monarch Larvae."

78. Ferber, "Risks and Benefits."

79. Ferber, "Risks and Benefits."; see also S. Milius, "New Studies Focus Monarch Worries," *Science News* 156 (18-25 December 1999): 391.

80. Ricki Lewis and Barry A. Palevitz, "GM Crops Face Heat of Debate," *The Scientist* 13 (11 October 1999): 1, <*www.the-scientist.com/yr1999/oct/index_991011.html*> (19 January 2000); see also Mary Beth Sheridan, "A Delicate Balancing Act in Mexico," *Los Angeles Times*, home edition, A section (29 February 2000).

81. Madhuri Kota et al., "Overexpression of the *Bacillus Thuringiensis* (*Bt*) CRy2Aa2 Protein … ;" Susan E. Scott and Mike J. Wilkinson, "Low Probability of Chloroplast Movement from Oilseed Rape (*Brassica Napus*) into Wild *Brassica Rapa*," *Nature Biotechnology* 17 (April 1999): 390-92; Dean Chamberlain and C. Neal Stewart, "Transgene Escape and Transplastomics," *Nature Biotechnology* 17 (April 1999): 330-31.

82. Angelika Hilbeck et al., "Effects of Transgenic *Bacillus Thuringiensis*

Corn-fed Prey on Mortality and Development Time of Immature *Chysoperla Carnea (Neuroptera: Chrysopidae*)," *Environmental Entomology* 27 (1998): 480-87.

83. Alan J. Gray and Alan F. Raybould, "Crop Genetics: Reducing Transgene Escape Routes," *Nature* 392 (16 April 1998): 653-54; see also C. L. Wraight et al., "Absence of Toxicity of *Bacillus thuringiensis* Pollen to Black Swallowtails under Field Conditions," *Proceedings of the National Academy of Sciences*, published online before print 6 June 2000, Object identifier 10.1073/pnas.130202097, <*http://www.pnas.org*>.

84. Gray and Raybould, "Crop Genetics: Reducing Transgene Escape Routes."

85. Mann, "Biotech Goes Wild."; Philip J. Regal, "Scientific Principles for Ecologically Based Risk Assessment of Transgenic Organisms," *Molecular Ecology* 3 (1994): 5-13, *www.psrast.org/pjrisk.htm*> (11 January 2000); Lemaux, "Plant Growth Regulators and Biotechnology."

86. James R. Cook, "Toward Science-Based Risk Assessment for the Approval and Use of Plants in Agriculture and Other Environments" (paper presented at the joint CGIAR/NAS Biotechnology Conference, Washington, D.C., October 1999, <*www.cgiar.org/biotechc/cook.htm*> (11 November 1999); Mann, "Biotech Goes Wild."

87. Royal Society, *Genetically Modified Plants for Food Use,* September 1998, <*www.royalsoc.ac.uk/policy/index.html*> (11 January 2000).

88. Regal, "Scientific Principles..."

89. Royal Society, *Genetically Modified Plants*.

90. See also Mark Sagoff, "What's Wrong with Exotic Species?" *Report from the Institute for Philosophy and Public Policy* 19 (Fall 1999): 16-23; A. J. S. Rayl, "Are All Alien Invasions Bad?" *The Scientist* 14 (20 March 2000), <*http://www.the-scientist.com/yr2000/mar/rayl_p15_000320.html*> (21 March 2000).

91. Royal Society, *Genetically Modified Plants*.

92. Daniell, "The Next Generation of Genetically Engineered Crops."; Royal Society, *Genetically Modified Plants*.

93. Royal Society, *Genetically Modified Plants*.

94. Sheppard, Lisa, "GMO Food Safety Risk is Negligible," College of Agricultural, Consumer and Environmental Sciences, University of Illinois at Urbana-Champaign, news release (23 November 1999), <*www.ag.uiuc.edu/news/articles/943382465.html*> (10 December 1999).

95. Lewis and Palevitz, "GM Crops Face Heat of Debate."

96. U.S. Senate Committee on Agriculture, Nutrition, and Forestry, *The Science of Biotechnology and Its Potential Applications to Agriculture: Hearing before the Committee on Foreign Relations*. 106th Cong., 1st sess., 6 October 1999 <*www.senate.gov/~agriculture/Hearings/Hear-*

ings_1999/buc99106.htm> (11 January 2000).

97. Royal Society, *Genetically Modified Plants*; National Center for Food Safety and Technology, The Biotechnology Information for Food Safety Database, <*www.iit.edu/~sgendel/fa.htm*> (11 January 2000).

98. U.S. Senate Committee on Agriculture, Nutrition, and Forestry, *The Science of Biotechnology and Its Potential Applications to Agriculture: Hearing.*; Kathleen Scalise, "New Solution for Food Allergies Effective with Milk, Wheat Products, Maybe Other Foods, UC Researchers Discover," University of California, Berkeley, news release (19 October 1997), <*www.urel.berkeley.edu/urel_1/CampusNews/PressReleases/releases/10_19_97a.html*> (5 January 2000).

99. Royal Society, *Genetically Modified Plants*.; Food and Agricultural Organization/World Health Organization, *Biotechnology and Food Safety Special Issues*, Report of a Joint FAO/WHO Consultation, Rome, 30 September-4 October 1996, <*http://www.fao.org/waicent/faoinfo/economic/esn/biotech/six.htm*> (12 June 2000); Robert May, "*Genetically Modified Foods: Facts, Worries, Policies and Public Confidence*," Briefing from the Chief Science Adviser, Sir Robert May FRS (February 1999), <*www.gn.apc.org/pmhp/dc/genetics/cso-gmos.htm*>; Dan Ferber, "Superbugs on the Hoof," *Science*, 288 (5 May 2000): 792-94; *Science*, "Corrections and Clarifications" (to Ferber, "Superbugs on the Hoof"), *Science* 288 (9 June 2000): 1751.

100. Andy Coghlan, "On Your Markers," *New Scientist* (20 November 1999), <*www.newscientist.com/nsplus/insight/gmworld/gmnews97.html*> (20 November 1999).

101. Royal Society, *Genetically Modified Plants*.; Keith Harding, "Biosafety Reviews: Biosafety of Selectable Marker Genes," Biosafety Information Network and Advisory Service Online, United Nations Industrial Development Organization, <*www.bdt.org.br/binas/index.html*> (12 June 2000).

102. See, e.g., Jonathan Williams, "Organic Farming in the Uplands of Mid Wales," Statement at Earth Options, Second "Look Out Wales" Environmental Forum, May 1998, <*www.wyeside.co.uk/expotec/jonathan_williams.htm*> (19 March 2000).

103. World Health Organization, *The World Health Report 1999*.

104. MacIlwain, "Access Issues."

105. Goklany, "Saving Habitat."; id., "Meeting Global Food Needs."

106. Greenpeace, "Stop Monsanto's Terminator Technology," press release (20 September 1998), <*www.greenpeace.org/~geneng/highlights/pat/98_09_20.htm*> (12 January 2000); Friends of the Earth, "FoE Supports Tory GM Moratorium Call: What about the Precautionary Principle Mr. Blair?" press release (3 February 1999), <*http://www.foe.co.uk/pubsinfo/infoteam/pressrel/1999/19990203170456.html*> (15 May 2000).

107. Friends of the Earth, "FoE Supports Tory GM Moratorium Call."; id., "FoE Remains Sceptical about Monsanto's Terminator Pledge," press release (5 October 1999), <*http://www.foeeurope.org/press/foe_remains_sceptical.htm*> (21 February 2000).

Indur M. Goklany, Ph.D., is currently the D & D Foundation Julian Simon Fellow at the Political Economy Research Center (PERC) in Bozeman, Montana, while on leave from the United States Department of the Interior's Office of Policy Analysis. His work as an independent scholar at PERC is not part of his official duties with that department and does not necessarily reflect its views or policies or of any other branch of the federal government. He has over 25 years of experience in dealing with environmental and natural resource science and policy issues. His current research interests are in investigating the role of technological change, economic growth, and trade in contributing to, as well as solving, problems related to biodiversity, land use, food supplies, and global warming.

Other publications available in this series:

151. **Enhancing Environmental Protection While Fostering Economic Growth,** Kenneth W. Chilton, March 1999
152. **Are Economic Growth and a Sustainable Environment Compatible?** Kenneth W. Chilton, September 1999
153. **Product Take-Back Systems: Mandates Reconsidered,** Lynn Scarlett, October 1999
154. **Estimating the Costs of Kyoto: Uncertainties and Assumptions Driving the Model Results,** Milka S. Kirova, December 1999
155. **Technology, Market Changes, and Antitrust Enforcement,** Dwight R. Lee and Richard B. McKenzie, February 2000
156. **Technology and a Safe Work Place**, Richard K. Vedder, July 2000

Additional copies are available from:

Center for the Study of American Business
Washington University
Campus Box 1027
One Brookings Drive
St. Louis, Missouri 63130-4899
Phone: (314) 935-5630
http://csab.wustl.edu

Washington
WASHINGTON·UNIVERSITY·IN·ST·LOUIS