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PRECAUTION WITHOUT PERVERSITY: A COMPREHENSIVE APPLICATION OF THE PRECAUTIONARY PRINCIPLE TO GENETICALLY MODIFIED CROPS©

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Abstract

The precautionary principle (PP) has sometimes been invoked to justify a ban on GM crops. This justification, however, takes credit for reducing potential public health and environmental risks that might result from a ban but ignores any blame for risks that the ban might generate or prolong. Contributing to such one-sided accounting is the fact that most formulations of the precautionary principle provide no guidance for evaluating a policy if it results simultaneously in uncertain benefits and uncertain harm. Accordingly, policy cures based on such one-sided applications of the PP could aggravate the underlying disease. This article develops a framework to evaluate policies where the net result might be ambiguous because their effects -- both beneficial and harmful -- are uncertain. This framework attempts to sort out competing claims on both sides of the ledger by considering, among other things, the nature, magnitude, and the certainty of the positive and negative effects of a ban, and the likelihood that a ban would reduce or aggravate those effects. The application of this framework shows that a ban on GM crops is likely to do more harm to public health (because a ban would retard reductions in global hunger, malnutrition, and diseases of affluence) as well as to the environment (because a ban would increase land, water and chemical inputs devoted to agriculture, further intensifying the major threats to global biodiversity). Accordingly, the article concludes that an even handed application of the PP requires that GM crops should be encouraged rather than banned, provided due caution is exercised. Corollaries to this result are: (a) a ban on GM crops would be contrary to the spirit and letter of the international Convention on Biological Diversity which aims to protect biodiversity, preferably using in situ conservation, and (b) a policy to ban all GM crops ought not to come under the purview of the Cartagena Biosafety Protocol.

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Indur M. Goklany[2]

1. Introduction

A popular formulation of the precautionary principle — and the one which I will use in this article — is that contained in the Wingspread Declaration (Raffensperger and Tickner 1999: 8):

> "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."

This principle captures much of the skepticism many environmentalists feel about technology (see, e.g., Goklany 1996). While some scholars (e.g., Morris 2000) claim that the PP derives from the 1970s' German articulation of *Vorsorgeprinzip* — translated as the "precaution" or "foresight" principle — it is essentially a wordy reformulation of every mother's admonition that it is "better to be safe than sorry" (see, e.g., Adler 2000). In the 1980s, various versions of the precautionary principle started to appear in international environmental declarations and agreements. By the time of the 1992 UNCED Conference in Rio de Janeiro, the PP was well-nigh ubiquitous: it was incorporated not only in Principle 15 of the Rio Declaration (UN 1992: 10) but in Article 3.3 of the United Nations Framework Convention on Climate Change (UNFCCC 1992), and in the preamble to

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the Convention on Biological Diversity (Glowka et al. 1994: 11). Out of these eventually emerged, in January 2000, the Cartagena Protocol on Biosafety to the Convention on Biological Diversity which repeatedly uses the precautionary principle as a basis for decision making and risk assessment with respect to the transboundary transfer (and associated handling and use) of genetically modified organisms (GMOs) that may have adverse effects on the conservation and sustainable use of biological diversity (CBD 2000). As Smith (2000) has noted, the Cartagena Protocol is seen as a major victory for the precautionary principle, and its advocates.

In keeping with its origins in technological skepticism, the mantra of the precautionary principle has also been increasingly invoked to justify, among other things, international controls, if not outright bans, of various technologies which — despite providing substantial benefits to humanity and, in some cases, to certain aspects of the environment — could also worsen other aspects of the environment or public health (Goklany 2000a). Among the technologies against which the PP has been invoked are DDT, a pesticide which has had spectacular success in reducing one of nature's dread diseases — malaria — worldwide, but which also has been associated with declines in the population of various avian species such as the bald eagle and the peregrine falcon (Goklany 2000b); fossil fuel combustion, on which much of the world's current prosperity and human well-being is based but which could contribute to global warming (Goklany 2000c); and GM crops, which promise a reduction in global hunger and malnutrition but which have also raised the specter of "frankenfoods" (FOE 1999a, Goklany 2000a).

In addition to the PP itself, the justifications for these policies all share something else: a common flaw. The flaw is that each of these justifications takes credit for the public health and environmental risks that might be reduced by implementing the policy, but they ignore those public health and environmental risks that the policy itself might generate or prolong. As a result, there is a risk that the above policy cures could be worse for humanity and the environment than the underlying diseases they seek to redress (Goklany et al. 2001, Goklany 2000a). This one sided application of the PP has been attributed to the fact that the principle itself provides no guidance on its application in situations where an action (such as a ban on GM crops) could simultaneously lead to uncertain benefits and uncertain harms (Goklany 2000a).

This article proposes to rectify this state-of-affairs by first developing a”framework” for applying the PP to policies whose outcomes might be ambiguous because their benefits might be offset in whole or in part by their harms. The article, which is based on a policy study published by the Weidenbaum Center, Washington University in St. Louis, Missouri (Goklany 2000d), focuses on applying the PP to a ban on GM crops.

In Section 2, I develop the “framework” for applying the PP in ambiguous situations. Next, I briefly survey the public health and environmental benefits and costs of GM crops (Sections 3 and 4). Then, I apply the framework to the broad range of consequences of a ban on GM crops to determine whether an unbiased and comprehensive application of the PP would justify such a ban (Section 5). Next, I examine whether a ban would be consistent with, or further the stated aims and objectives of, the international Convention on Biological Diversity (Section 6), and whether GM crops (as a class) could or should be banned under the Cartagena Biosafety Protocol (Section 7).

2. A Framework for Applying the Precautionary Principle Under Competing Uncertainties

Few actions are either an unmitigated disaster or an unadulterated benefit, 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 (or costs) to public health and the environment? Therefore, prior to 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 a set of criteria to construct a precautionary “framework.”

The first of these criteria is the *human mortality criterion*, i.e., the threat of death to any human being — no matter how lowly that human — outweighs similar threats to members of other species — no matter how magnificent that species. Moreover, in general, other non-mortal threats to human health should take precedence over threats to the environment, although there might be exceptions based on the nature, severity and extent of the threat. I will call this the *human morbidity criterion*. These two criteria can be combined into the *public health criterion*.

However, in instances where an action under consideration results in both potential benefits and potential harms 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 propose five such criteria:

! 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 (Cropper and Portney 1992). 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, between 1995 and 1999 estimated U.S. deaths due to AIDS dropped by over two-thirds (from 50,610 to 16,273) even though estimated cases increased by almost half (from 216,796 to 320,282) (CDC

2000, Tables 23 and 26). Thus if an HIV-positive person in the United States did not succumb to AIDS in 1995, because of the advances in medicine there was a greater likelihood in 1998 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 article, 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.

Ideally, each criterion should be applied, one at a time, to the various sets of public health and environmental consequences of the action under review (minus, for each category, the consequences of persisting with the *status quo*, or whatever the other options might be). Such an approach could work relatively easily if the factors critical to each criterion were kept constant, except the ones related to the criterion under evaluation. But since the various factors are rarely equal, the net effects (on each of the sets of consequences) usually have to be evaluated by applying several of the criteria simultaneously. Then, if the results are equivocal with respect to the different sets of consequences, one should apply the human mortality and morbidity criteria. Thus, if the action, for example, might directly or indirectly increase net human mortality but improve the environment by, for instance, increasing the recreational potential of a water body, then the action ought to be rejected. Of course, there will be instances where no cut-and-dried answer will emerge readily; for example, if an action might reduce cases of a non-lethal human disease while at the same time potentially killing a large number of animals. In such cases, in addition to considering factors such as the nature, severity and curability of the disease, cost of the disease and/or treatment, and numbers of human and other species affected (factors subsumed in the previously specified criteria, namely, the adaptation, irreversibility and expectation value criteria), decision making should also consider factors such as the abundance of the species, whether the species is threatened or endangered, and so forth.

In the following, I will outline the potential benefits and costs to public health and the environment due to research, development and commercialization of GM crops before applying the relevant criteria to determine the appropriate policy pursuant to the precautionary principle.

3. The Potential Benefits of Bioengineered Crops

3.1 Environmental Benefits. Agriculture and forestry, in that order, are the human activities that have the greatest effect on the world's biological diversity (Goklany 1998a). Today, agriculture alone accounts for 37% of global land area (FAO 1999a), 70% of water withdrawals and 87% of consumptive use worldwide (UNCSD 1997). It is also the major determinant of land clearance and habitat loss worldwide. Between 1980 and 1995, for instance, developing countries lost 190 Mha of forest cover mainly because their increase in agricultural productivity was exceeded by growth in food demand, while developed countries increased their forest cover by 20 Mha because their productivity outpaced demand. Agriculture and, to a lesser extent, forestry also affects biodiversity through water pollution and atmospheric transport, for example, by release of excess nutrients, pesticides and silt into the environment (Wilcove et al. 1998, Goklany 1998a).

Demand for agricultural and forest products is almost certainly going to increase substantially. The world's population will almost inevitably grow from about 6 billion today to, perhaps, between 10 and 11 billion in 2100, an increase of 70 to 80%. The average person is also likely to be richer, which ought to increase food demand per capita. Accordingly, the predominant future environmental and natural resource challenge for the globe is probably the problem of meeting the human demand for food, nutrition, fiber, timber and other natural resource products while conserving biodiversity (Goklany 1995,1998a, 1999a, 1999b, 2000e).

The question is whether biotechnology can help or hinder reconciling these often opposing goals (Goklany 1999a). 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.

3.1.1 Decrease in Land and Water Diverted to Human Uses. The U.N.'s latest most likely estimate is that global population, which hit 6 billion in 1999, will grow to 8.9 billion in 2050 (UNPD 1999). Figure 1, based on the methodology outlined in Goklany (1998a, 1999a), provides estimates of the additional land that would need to be converted to cropland from 1997 and 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 (Goklany 1998a) – the entire increase in production (106% under the above assumptions of growth in population and food demand) would have to come from an expansion in global 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 (FAO 2000). Much of that expansion would necessarily have to come at the expense of forested areas (Goklany 1998a). It would lead to massive habitat loss and fragmentation, and put severe pressure on the world's remaining biodiversity, and on *in situ* conservation.

On the other hand, a productivity increase of 1.0% per year, equivalent to a cumulative 69% increase from 1997 to 2050, would reduce the net amount of new cropland required to meet future demand to 325 Mha. Such an increase in productivity is theoretically possible without resorting to biotechnology, provided sufficient investments are made in human capital and research and development, extension services, infrastructure expansion (to bring new lands, where needed, into production and integrate it with the rest of the world's agriculture system), inputs such as fertilizers and pesticides, and the acquisition and operation of technologies to limit or mitigate environmental impacts of agriculture (Goklany 1998a, 1999a).

A 1.0% per 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% per year between 1961-63 and 1996-98 (FAO 2000). What is more important, 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; Goklany 1998a, 1999a). Merely increasing the 1996-98 average cereal yields in developing and transition nations to the level attained by Belgium-Luxembourg (the country group that had the highest average yield, i.e., the yield ceiling, YC) would have increased global production by 141% (calculated from FAO 2000), while increasing the average global cereal yield (2.96 T/ha in 1996-98; FAO 2000) to YC (7.80 T/ha in 1996-98) would increase global cereal production by 163%. Notably, the theoretical maximum yield is 13.4 T/ha or 350% greater than the average global cereal yield in 1996-98 (Linnemann et al. 1979).

Specifically, conventional (i.e., non-bioengineering) methods could be used to increase net productivity in the food and agricultural sector from farm to mouth by: (a) further limiting pre-harvest crop losses to pests and diseases, which currently reduce global yields by an estimated 42% (Oerke et al. 1994); (b) increasing fertilizer use; (c) liming acidic soils; (d) adapting high yielding varieties to specific locations around the world, although many scientists believe that opportunities to further increase yields through conventional breeding techniques are almost tapped out (Conway and Toennissien 1999, Mann 1999a); and (e) by reducing post-harvest and end-use losses (Goklany and Sprague 1991), which are estimated at about 47% worldwide (Bender 1994). Moreover, precision farming could help reduce chemical and water use without reducing yields, which would reduce many of the adverse effects of modern agriculture.

Productivity improvements could come much more rapidly and more surely if biotechnology is used. Biotechnology could more easily and quickly reduce current gaps between average yields and yield ceilings, and yield ceilings and the theoretical maximum yield, as well as push up the theoretical maximum yield. This begs the question as to whether environmental costs of such productivity increases will also increase and whether the latter 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 goes up from 1.0% to 1.5% per year, then cropland could actually be *reduced* by 98 Mha rather than increased by 325 Mha (relative to 1997 levels), while at the same time meeting the increased food demand of a larger and richer population. This corresponds to a net increase in productivity of 30% in 2050 due to biotechnology alone. And if productivity is increased 2.0% per year, then by 2050 at least 422 Mha of current cropland could be returned to the rest of nature or made available for other human uses. This corresponds to a net improvement in productivity by 2050 of 69% due to biotechnology (Figure 1).

Several biotechnological crops, currently in various stages between research and commercialization, could increase yields and, more importantly, put more food on the table per unit of land and water diverted to agriculture. Such crops, which could be particularly useful in developing nations, include:

! *Cereals which are tolerant of poor climatic and soil conditions*; specifically, cereals which are tolerant to aluminum (so that they can grow in acidic soils), drought, high salinity levels, submergence, chilling and freezing (De la Fuente et al. 1997, Apse et al. 1999, Kasuga et al. 1999, Swaminathan 1999, Conway and Toennissien 1999, Moffat 1999a, Zhang 1999, Pennisi 1998, Prakash 1998a; see, also, Jaglo-Ottosen et al. 1998) . The ability to grow crops in such conditions could be critical for developing countries: 43% of tropical soils are acidic (World Bank 1994); more cropland is lost to high salinity than is gained through forest clearance; and salinity has rendered one-third of the world's irrigated land unsuitable for growing crops (Frommer et al. 1999). 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 (1999) experiments, 96.2% of GM plants survived freezing, compared to 9.5% for the wild-type plant. Corresponding numbers for drought were 76.7% vs. 1.8% and, for salinity stress, 78.6% vs. 17.9%.

- *Rice which combines the best traits of the African and Asian varieties*. This rice combines the former's ability to shade out weeds when young with the high yield capacity of the Asian variety (Conway and Toennissien 1999). 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 elsewhere (Goklany 1998a).
- *Rice with the property of being able to close stomata more readily* (Mann 1999a). This ought to increase water use efficiency and net photosynthetic efficiency. Both aspects will be useful under dry conditions – conditions which, moreover, may get more prevalent in some areas under global warming.
- *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 (Ku et al. 1999, Edwards 1999, Conway and Toennissien 1999). 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 (Mann 1999b).
- *Maize, rice and sorghum with resistance to Striga, a parasitic weed which could decimate yields in Sub-Saharan Africa* (Mann 1999c, MacIlwain 1999, Conway and Toennissien 1999).

- *Rice with the ability to fix nitrogen* (IRRI 1999).
- *Rice and maize with enhanced uptakes of phosphorus and nitrogen* (Conway and Toennissien 1999, Prakash 1998b, Inside Purdue 1998). Notably, these two crops account for 20% of global cropland.
- *Rice, maize, potato, sweet potato, and papaya with resistance to insects, nematodes, bacteria, viruses, and fungi*. For instance, papaya, which, for instance, had been ravaged in Hawaii by the papaya ringspot virus, has now made a comeback due to a bioengineered variety resistant to that virus (Conway and Toennissien 1999, Ferber 1999).
- *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 GM cassava could, it is claimed, increase yields 10-fold (Moffat 1999b). Also, because cassava naturally contains substances that can be converted to cyanide, it has to be adequately prepared before consumption. Work is proceeding on producing a genetically modified (GM) cassava which would be less toxic (Conway and Toennissien 1999).
- *Spoilage-prone fruits bioengineered for delayed ripening, thereby increasing their shelf life and reducing post-harvest losses*. These include bananas and plantains, important sources of food for many African nations (Conway and Toennissien 1999), and, in the U.S., melons, strawberries and raspberries (Lemaux 1999).
- *Crops bioengineered to reduce the likelihood of their seed pods shattering*, which reduces yields of crops such as wheat, rice and canola. It is estimated that this could increase canola yields, for instance, by 25% to 100% (Liljegren et al. 2000).
- *High lysine maize and soybeans, maize with high oil and energy content, and forage crops with lower lignin content*, which ought to improve livestock feed and reduce the overall demand for

land needed for livestock (Mazur et al. 1999, Conway and Toennissien 1999).

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, and free up those resources for the rest of nature.

3.1.2 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 would also reduce the area subject to soil erosion from agricultural practices which, in turn, would limit associated environmental effects on water bodies and aquatic species and reduce loss of carbon sinks and stores into the atmosphere. Furthermore, many of the same GM crops could also directly reduce nutrients and pesticides released into the environment (Goklany 2000d). 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 U.S., only 18% of the nitrogen and 30% of the phosphorus in fertilizers are incorporated into crops, between 10 and 80% of the nitrogen and 15% of the phosphorus end up in aquatic ecosystems, and much of the remainder accumulates in the soil, to be later eroded into aquatic systems (Carpenter et al. 1998). Nitrogen-fixing crops would reduce reliance on fertilizers and, thereby, reduce ground and surface water pollution, risks of chemical spills, and atmospheric emissions of nitrous oxide (N_2O), a greenhouse gas that, pound for pound over a 100-year period, is 310 times more potent a greenhouse gas than is CO_2 (IPCC 1996a).

- *Crops resistant to viruses, weeds, and other pests,* e.g., *Striga*-resistant maize, rice and sorghum. Examples also include various *Bt* crops which contain genes from the *Bacillus thuringiensis* bacterium, which has been used as an insecticide (as a spray) for four decades. One evaluation of *Bt* cotton in the U.S. estimates its planting on 2.3 million acres in 1998 (as opposed to using the conventional variety) reduced chemical pesticide use by over a million pounds, increased yields by 85 million pounds and netted farmers $92 million (Ferber 1999). The usage of *Bt* maize which was planted on 14 million acres in the U.S. reduced pesticide spraying on 2 million of those acres. Developing countries also can reduce pesticide usage by using pest resistant crops. India is the world's third largest producer of cotton. Cotton occupies only 5% of its land, yet cotton farmers buy about 50% of all pesticides used in the country (Prakash 1999). 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% yield increase despite suspension of any spraying (Hindu Business Line 2000).
- *Low phytic acid corn and soybean and phytase feed,* which help livestock better digest and absorb phosphorus. This would 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 (Grabau Laboratory 2000, Mikesell 1999, CeresNet 1999). It 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" soybean, which

is engineered to be tolerant to glyphosate. Such crops could help reduce the amount, toxicity and/or persistence of pesticides employed. Planting of these crops seems to have reduced application of more hazardous and longer lasting herbicides (e.g., acetochlor), although overall herbicide use may have increased (Ferber 1999). Second, such crops would also increase yields, while facilitating no-till cultivation which, by stemming soil erosion, protects future agricultural productivity. Moreover, erosion 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.

3.1.3 Other Environmental Benefits of Bioengineered Plants and Trees. Crops can also be engineered to directly cleanup environmental problems. For instance, GM plants can be used for bioremediation by developing crops that selectively absorb various metals and metal complexes such as aluminum, copper and cadmium from contaminated soils (Moffat 1999b). 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% less lignin and 15% 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:cellulose ratio of about 1:2. Overall, 15 percent more pulp may be produced from the same amount of wood. Moreover, the GM trees are 25-30% taller. Thus, the requirements of 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 (MTU 1999).

Other potential applications of biotechnology which could reduce environmental impacts include production of biodegradable plastics using oilseed rape and colored cotton (which could reduce reliance on synthetic dyes) (Lawrence 1999).

3.2 Public Health Benefits. Having sufficient quantities of food is often the first step to a healthy society (WHO 1999a, Goklany 1999b). 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% (FAO 1999a). Thus, despite a 40% increase in population between 1969-71 and 1994-96, chronic undernourishment in developing countries dropped from 35% to 19% of their population (FAO 1999b) which, in turn, helped lower global infant mortality rates from 156 to 57 per 1,000 live births (between 1950-55 and 1998), increase life expectancies from 46.5 to 65.7 years (between 1950-55 and 1997), and enable the average person to live a more fulfilling and productive life (WHO 1999a, UNDP 1999, Goklany 1999b).

Despite the 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 extent or severity.

Table 1 shows that globally about 825 million people currently are undernourished, i.e., cannot meet their basic needs for energy and protein (FAO 1999b). Reducing these numbers over the next half-century while also reducing pressures on biodiversity despite anticipated population increases of 1.3 to 4.7 billion (UNPD 1999), requires increasing the quantity of food produced per unit of land and water. As discussed above, GM crops could help in this struggle.

But increasing food quantity is not enough. Improving the nutritional quality of food is now just as important. The diets of over half the world's population are deficient in iron, vitamin A or other micronutrients (see Table 1). Such deficiencies can cause disease, if not death (WHO 1999a, FAO 1999b). About 2 billion people do not have enough iron in their diet, 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 (WHO 1999b). Through the cumulative effect of these deficiencies, in 1995, malnutrition was responsible for 6.6 million or 54% of the deaths worldwide in children under five years of age, stunting in 200 million children, and clinical xerophthalmia in about 2.7 million people (WHO 1999c).

In addition to ensuring 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" which is rich in beta-carotene, a precursor to vitamin A, and crossed it with another bioengineered strain rich in iron and cysteine (which allows iron to be absorbed in the digestive tract). Such rice would help reduce vitamin A and iron deficiency related deaths and diseases in the developing world. Iron-fortified rice — whether golden or not — would also 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 might be reduced (Gura 1999, Guerinot 2000, Ye et al. 2000; see, also, Goto et al. 1999).

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 (Moffat 1999b, Smaglik 1998). 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. In 1998, according to the World Health Organization (1999a), these diseases accounted for 4.8 million or 60% of the total deaths in high income countries, and 14.9 million or 32% of deaths in the low and middle income countries (Table 1). Several GM crops can help reduce this toll. For instance, genetically enhanced soybeans that are lower in saturated fats are already in the market. The International Food Information Council (1999) also notes that biotechnology could also make soybean, canola and other oils and their products, such as margarine and shortenings, more healthful. Bioengineering could also produce peanuts with improved protein balance; tomatoes with increased antioxidant content; potatoes with higher starch than conventional potatoes, which ought to reduce the amount of oil absorbed during processing of foods like French fries or 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.

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 (Munkvold and Hellmich 1999). Morton (2001) also argues that GM *Bt* food crops are safer than conventional crops sprayed with *Bt* because the sprays contain several toxins which could affect both insects and mammals, while the GM variety contains a single toxin known to be harmful to insects but not to mammals. Thus, *Bt* corn, whether used as food for humans or feed for livestock, may be safer and healthier than conventional corn.

GM plants may also be able to save life and limb, if they can be successfully engineered to biodegrade explosives around land mines and abandoned munitions sites (Bolin 1999, French et al. 1999).

Finally, to the extent pest resistant GM plants can, as noted previously, reduce the amount, toxicity and/or persistence of pesticides used in agriculture (by themselves or as parts of integrated pest management systems), that would reduce accidental poisonings and other untoward health effects on farm workers. For instance, there apparently have been instances of food poisoning and human infections from Bt sprays but none (so far) from Bt crops (Morton 2001).

4. The Potential Costs of Bioengineered Crops

4.1 Adverse Environmental Consequences. The major environmental concerns regarding GM crops are those related to crops which are designed to be resistant to pests or 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 argued that it is of greater concern with *Bt* plants on the basis that 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, which could increase the chances of developing *Bt*-resistant pests (Gould 1998; see, also, Walliman 2000). Moreover, some laboratory studies suggest that target pests may evolve resistance more rapidly than had previously been thought possible (Liu et al. 1999, Agbiotechnet 1999). However, subsequent studies from Arizona, Mississippi, and Australia indicate that contrary to these prognostications, bollworm, for instance, did not increase its resistance to *Bt* toxin produced by a GM *Bt* cotton (Tabashnik et al. 2000, Kershen 2001).

It has also been argued that the only known insect resistance to *Bt* is due to *Bt* sprays (Morton 2001). This has been attributed to the adaptation of conventional strategies (developed to deter pest resistance due to conventional pesticide) to GM crops. Such strategies include ensuring plants deliver high doses of *Bt*, while simultaneously maintaining refuges for non-*Bt* crops to ensure pest populations remain susceptible to *Bt*. In fact, EPA has established the requirement that *Bt* corn farmers plant 20% of their land in non-*Bt* corn, as refuges. For *Bt* corn grown in cotton areas, farmers must plant at least 50% non-*Bt* corn (EPA 2000a). EPA also requires expanded monitoring to detect any potential resistance. Other strategies to delay development of pesticide resistance include crop rotation (Gould 1998), developing crops with more than one toxin gene acting on separate molecular targets (Conway 2000) and inserting the bioengineered gene into the chloroplast since that ought to express *Bt* toxin at higher levels (Daniell 1999, Kota et al. 1999). Notably, farmers have an economic stake in implementing such adaptive strategies so that their crop losses to pests are kept in check in the long, and 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 was consumed by non-target organisms susceptible to the *Bt* toxin (Losey et al. 1999, Walliman 2000, Saxena et al. 1999). Losey et al. (1999) in a laboratory study indicated a 44% mortality rate for Monarch butterfly larvae fed on milkweed dusted with *Bt* corn pollen compared to zero for the control case (which used milkweed dusted with ordinary pollen). In a more sophisticated study, Jesse and Obrycki (2000) showed a 20% mortality rate to Monarch butterfly larvae fed in the laboratory with leaves exposed to pollen in or near a field of Bt plants. However, whether -- and the extent to which -- the Monarch butterfly population would be affected in the real world is a matter of debate (Ferber 1999, Richard 2000). One study suggests that under a worst-case scenario as much as 7% of the North American population (estimated at 100 million) may die, although the real-world effect would probably be smaller (Ferber 1999; see, also, Milius 1999). Some have also argued that the major threat to Monarchs is the habitat loss in their wintering grounds in Mexico (Lewis and Palevitz 1999; see, also, Sheridan 2000), which is a result of pressure from a growing population in need of land.

Notably, in a recent analysis, EPA (2000b) concluded that based on their examination, “the weight of evidence” indicates “no hazard to wildlife from the continued registration of Bt crops.” The Agency also concluded that continued cultivation of Bt corn is unlikely to “cause harmful widespread effects to monarch butterflies at this time.” It also noted that the only endangered species of concern are in the Lepidoptera and Coleoptera group (i.e., butterflies, moths and beetles), but the majority of these species have very restricted habitat range and do not feed in, or close to the *Bt* crop planting areas. 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 (Kota et al. 1999, Scott and Wilkinson 1999, Chamberlain and Stewart 1999).

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, which ate maize borers fed with *Bt* maize were more likely to die (Hilbeck et al. 1998), but the real-world significance of this has also been disputed based on the long history of *Bt* spraying on crops and other studies which showed beneficial insects essentially unharmed by such spraying, particularly under field conditions (Gray 1998; Wraight et al. 2000).

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.” This would have an adverse economic impact on farmers. It would reduce crop yields and detract from the very justification for using such GM crops (Gray and Raybould 1998). Clearly, the farmer has 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, as is the case in the U.S. for sorghum, oats, rice, canola, sugar beets, carrots, alfalfa, sunflowers and radish (Mann 1999c, Regal 1994, Lemaux 1999). However, the most common GM crops, namely, soybeans or corn, have no wild U.S. relatives (Cook 1999, Mann 1999c). Moreover, as the Royal Society (1998) pointed out in its assessment of this issue, centuries of conventional breeding have rendered a number of important crops, e.g., maize and wheat, “ecologically incompetent” in many areas. It also noted that despite the use of conventionally-bred herbicide tolerant plants, there has been no upsurge in problems due to herbicide tolerant weeds (Royal Society 1998). While these theoretical arguments by themselves do not guarantee safety (Regal 1994), they seem confirmed by Crawley et al.’s (2001) 10-year long British study of four different herbicide tolerant or pest resistant GM crops (oilseed rape, corn, sugar beet, and potato) and their conventional counterparts grown in 12 different habitats. This study indicated that within four years, all plots of rape, corn and beet had died out naturally. Only one plot of potatoes survived the tenth year, but that was a non-GM variety. In other words, GM plants were no more invasive or persistent in the wild than their conventional counterparts. Moreover, had any herbicide tolerant or pest resistant weeds begun to spread, available crop management techniques (such as another herbicide) could have been used to control them.

The Crawley et al. study also provides reassurance with respect to another potential environmental concern, namely, that herbicide tolerant or pest resistant “superweeds” could invade natural ecosystems. It confirms that such GM plants do not have a competitive advantage in a natural system unless that system is treated with the herbicide in question. But if it were so treated, would it still qualify as a natural system? Moreover, if it had to be treated, another herbicide to which the so-called superweed is not resistant could be used. On the other hand, if the area is not treated with the herbicide in question, what difference does it make to the ecosystem whether the weed is tolerant? And what is the significance of “genetic pollution” with respect to ecosystem function and biodiversity? Would gene escape affect ecosystem function negatively? Does gene escape diminish or expand biodiversity?

To bring this issue into focus, consider the case of human beings: if an Indian from Calcutta comes to Washington, DC, and has an offspring with a native-born American would that not, as the term has been used, be considered genetic pollution? (Not very long ago, xenophobes labeled that, miscegenation.) Does that diminish, or expand, biological diversity? Is such genetic pollution acceptable for human beings, but not for other species? But if the answer varies with the species, it raises questions about the validity of the notion that gene escape can be equated to pollution — genetic, or otherwise (Goklany 2000a; see, also, Sagoff 1999, Rayl 1999, and, for a different viewpoint, Johnson 1999)

Also, genes may escape from GM crops to non-GM crops of the same species. If this were to occur, it would be unpopular with organic farmers, who are afraid it might "adulterate" their produce, as well as producers and farmers of GM seeds, who are not eager to have someone else profit from their investments. Crawley et al.'s study is consistent with the Royal Society's (1998) prognosis that because more crops (including corn, sorghum, sugar beet and sunflower) are now grown from hybrid seeds, that provides a measure of built-in security against such gene transfers. Moreover, the chances of such gene escape can be further reduced by maintaining a buffer between the two crops.

Of course, gene escape could be limited with greater certainty 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 their spread through pollen or fruit, as well as prevent root leakage (Daniell 1999, Royal Society 1998).

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 and other environmental benefits of reduced conversion of habitat to cropland, and decreased use of chemical inputs.

4.2 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 (Royal Society 1998). In fact, an estimated 4% of human diet is composed of DNA (Chassy and Sheppard 1999), and an average adult Briton consumes 150,000 km of DNA in an average meal (Lewis and Palevitz 1999). Moreover, it is unclear whether in reality consuming, for instance, beans which have been genetically 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 1-3% of the adults and 5-8% of the children in the U.S. suffer from food allergies, and each year, food allergies cause 135 fatalities and 2,500 emergency room visits (Buchanan 1999). This concern regarding allergic reactions to GM foods can be traced to pre-commercialization tests conducted by Pioneer Hi-Bred which showed that a soybean which 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. Notably, several databases of known allergens could be used to help identify problematic GM products before they are developed (Royal Society 1998, Gendel 1999). 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 (Buchanan 1999, Scalise 1997).

Yet another potential negative effect on public health is that antibiotic resistant "marker" genes which 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, by comparison with 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 (Royal Society 1998; see, also, FAO/WHO 1996, May 1999, Ferber 2000, *Science* 2000).

5. 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 criteria outlined in the framework presented in Section 2 for evaluating actions which could result in uncertain costs and uncertain benefits. Ideally, each criterion should be applied, one at a time, to the human mortality, the non-mortality public health, and the non-public-health-related environmental consequences of GM crop use (or non-use). However, since there are variations in the severities, certainties and magnitudes associated with the various competing costs and benefits regarding each of these sets of consequences, one may have to apply several criteria simultaneously.

5.1 Public Health Consequences. Population could increase 50% between 1998 and 2050 (from 5.9 billion to 8.9 billion, according to the U.N.'s best estimate). Hence, by 2050, one ought to expect that undernourishment, malnutrition and their consequences on death and disease would also increase by 50% worldwide, if global food supply increases by a like amount and all else remains equal. Thus, according to Table 1, which provides estimates for the prevalence of such problems for the mid- to late-1990s, 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 of hunger and malnutrition, and the degree of certainty attached to their public health consequences, one can state with confidence that limiting GM crops will, by limiting the rate at which food production can expand, almost certainly increase death and disease, particularly among the world's poor.

GM crops could also reduce or postpone deaths due to diseases of affluence. While the probability that might occur is lower than that of reducing deaths due to hunger and malnutrition, the expected number of deaths postponed could run into the millions. A 10% decrease, for instance, in the 15 million annual deaths nowadays due to cancer, ischemic and cerebrovascular diseases translates into 1.5 million lives saved each year (see Table 1). And these numbers could increase in the future as populations increase and become older.

By contrast, the negative public health consequences of ingesting GM foods are speculative (e.g., the effects due to ingesting transgenes), relatively minor in magnitude (e.g., a potential increase in antibiotic resistance), or both (e.g., increased incidence of allergic reactions). Moreover, it is possible to contain, if not eliminate, the effects of even those 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 which has been used to develop about a dozen GM crops, including maize, wheat, rice, sugar beet, oilseed rape, cotton and sunflowers (Coghlan 1999). With additional research, it ought to be possible to devise alternative marker genes for other crops or develop practical methods to remove or repress antibiotic resistant marker genes (Royal Society 1998, Harding 1998).

Thus, based on the *uncertainty, expectation value* and *adaptation criteria* applied either singly or in conjunction, the use of GM must be favored over its non-use. Hence, 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” (see, e.g., Williams 1998). 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 the latter’s food production. At present, net cereal imports of the developing countries exceed 10% of their production. Without trade (and aid) which moves the surplus production in developed countries voluntarily to developing countries suffering from food deficits, 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. And, as already noted, developing countries’ food deficits are only expected to increase in the future because of high population growth rates and, possibly, 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 it is today (Goklany 1998a, 1999a).

Also, the above argument against GM crops implicitly assumes that such crops will provide little or no public health benefits to the inhabitants of developed countries. (Environmental benefits are addressed below, in Section 5.2.) As noted in Section 3.2, 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. These diseases, which are major causes of premature death globally, currently kill about 4.8 million annually in the developed countries (WHO 1999a, Table 1). Even a small reduction in these numbers due to GM crops would translate into relatively large declines in their death tolls. Moreover, the health benefits of "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.

Another 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, it is unnecessary to increase food production; ergo, there is no compelling need for biotechnology (MacIlwain 1999). Significantly, this argument tacitly acknowledges that GM crops would boost production (and productivity). While this part of the argument is valid, it still has several flaws. First, while unequal access is a perennial problem — and which continues to persist despite the successes of conventional agriculture — the argument misses the point. The case for bioengineered crops is not that it is the one and only solution for solving hunger and malnutrition. Increasing food production and improving access are not mutually exclusive. It should be sufficient that GM crops can contribute to the solution, and that they are among the most efficient solutions for that problem.

Notably, conventional agriculture has been relatively successful in improving global access to food. This is obvious from the fact that hunger and malnourishment have declined substantially in the past few decades despite a substantial increase in population (see Section 3.2). The principal reasons for these improvements are production increases which outstripped population growth and brought food prices down worldwide; economic growth, which made food more affordable to all and sundry, particularly in developing countries; investments in infrastructure, which enable rapid and efficient distribution of agricultural products; and greater democratization, which increases the political accountability of rulers to those ruled (Goklany 1998a, 1999a). Although GM crops (in comparison with conventional crops) are unlikely to directly increase democratization or increase economic growth, they can, as the anti-GM crop argument (that "there is sufficient food") seems to recognize, boost productivity more rapidly and by larger amounts which would further increase food availability and reduce costs to consumers. Moreover, one of the problems contributing to poor distribution is spoilage of crops before they are consumed. As noted, various GM crops could increase shelf life, and reduce spoilage and wastage. Thus while GM crops can not guarantee equal access, it can improve access for the poorer segments of society more rapidly than can conventional crops.

Second, if the argument that there is sufficient food is truly a compelling one against GM crops then it should be equally valid for increases in production using conventional technologies, and perhaps developing countries like India and Bangladesh should forego increasing agricultural productivity altogether, and focus only on improving access and distribution. For obvious reasons, no one makes this argument. Third, this argument completely overlooks the fact that GM crops can improve the nutritional quality, and not merely the quantity of food, which as Table 1 shows can contribute substantially to reductions in human mortality and morbidity.

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

5.2 Environmental Consequences. 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- or transaction-free distribution system and a magical equalization of income) or whether it is four times that (possibly due to runaway population growth). And regardless of the level of demand, limiting GM crops would lower crop and forest yields per unit of land and water used. As Figure 1 shows, to compensate for the lower yields, more land and water would have to be pressed into mankind's service, leaving that much less for the rest of nature (Goklany 1998a, 1999a).

Reductions in the amount of land and water available for the rest of nature would be further aggravated by the fact that the price of land and water, relative to other goods, would necessarily rise, as would the opportunity costs for these resources (Goklany 1998a). This mean that the socioeconomic costs of setting aside land or water for conservation and preservation of nature would increase, further inhibiting *in situ* conservation of species and biodiversity, which is one of the major goals of the Convention on Biological Diversity beyond one of merely conserving biodiversity itself (Glowka et al. 1994: 11; see Section 6, below).

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, more importantly, persevere with vegetarian diets, thereby reducing the additional demand meat-eating places on land and water. In addition, giving up GM crops will, more likely than not, further increase pressures on biodiversity due to excess nutrients, pesticides and soil erosion. Finally, reduced conversion of habitat and forest to crop and timber land coupled with reduced soil erosion due to increased no-till cultivation would further limit deterioration of water quality and losses of carbon reservoirs and sinks.

Arrayed against these benefits to ecosystems, biodiversity, and carbon stores and sinks, are the environmental costs of limiting pest resistant and herbicide tolerant GM crops *minus* the environmental costs of conventional farming practices. These costs include a potential increase in the diversity of the flora and fauna associated with or in the immediate vicinity of GM crops if they are more effective in reducing 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 of the use or non-use of GM crops, one must conclude, based on the *uncertainty* and *expectation value criteria*, that the precautionary principle requires the cultivation of GM crops. On net, GM 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.

It may be argued that although gene escape to "natural" ecosystems might be a low probability event, it may cause 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 that would minimize the possibility of gene transfer to weeds and non-GM plants without diminishing any of the public health or environmental benefits of GM crops. Notably, some of the same groups that profess environmental concerns about genetic pollution subjected terminator technology to unbridled criticism (Greenpeace 1998, FOE 1999b). Clearly, in these groups' policy calculus, the potential environmental costs of GM crops are outweighed by the presumed negative economic consequences to farmers due to their inability to propagate GM crops from sterile seeds, and these groups' antipathy toward multinationals' profits.

It is debatable whether putting antipathy to profits ahead of public health or the environment is any more commendable than putting profits ahead of them. It certainly does not advance either human or environmental well-being.

6. Would a Ban on GM Crops Further the Convention on Biological Diversity's Goals?

The above analysis indicates that banning GM crops would more likely than not magnify threats to biodiversity and *in-situ* conservation. But the preamble to the Convention on Biological Diversity (CBD) states that "it is vital to anticipate, prevent and attack the causes of significant reduction or loss of biological diversity at source," (Glowka et al. 1994: 10) and that "the fundamental requirement for the conservation of biological diversity is the *in-situ* conservation of ecosystems and natural habitats and the maintenance and recovery of viable populations of species in their natural surroundings" (Glowka et al. 1994: 11). Article 1 of the CBD also identifies as the first of its various objectives, "the conservation of biological diversity." Thus a ban on GM crops would directly counter the Convention's *raison d'etre*.

Banning GM crops would also contradict the letter of the CBD. Article 8(d), which addresses *in situ* conservation, requires that "[each contracting party shall, as far as possible and as appropriate] ...[p]romote the protection of ecosystems, natural habitats and the maintenance of viable populations of species in natural surroundings" (Glowka et al. 1994: 39-41). Moreover, a GM ban would also make it harder to satisfy the requirements of Article 8(a) which requires contracting parties to "[e]stablish a system of protected areas or areas where special measures need to be taken to conserve biological diversity" (Glowka et al. 1994: 39) because, as noted above, there would be less land and water available for *in situ* conservation and, what would be available, would be socially and economically costlier to obtain and maintain (Goklany 1998a).

7. Would a Ban on GM Crops Advance the Cartagena Biosafety Protocol's Goals?

Both the objective and scope of the Cartagena Biosafety Protocol (Articles 1 and 4, respectively) are specifically limited to GM organisms (GMOs) "that may have adverse effects on the conservation and sustainable use of biological diversity, taking also into account risks to human health" (CBD 2000). But we have seen that *in the aggregate*, by contrast with conventional crops, GM crops are unlikely to have adverse impacts on the environment, conservation, sustainable use and human health. Thus, it can be argued that the case for subjecting GM crops (at least, as a class) to any requirements under the Protocol is, at best, weak. And it looks even weaker when one considers the sources of the Protocol's authorities.

As noted in its preamble and Article 1, the Protocol derives its authority regarding the regulation of the transfer, handling, and use of GMOs largely from Principle 15 of the Rio Declaration, which is a statement of the precautionary principle (UN 1992: 10), and various articles of the CBD, namely, Articles 8 (g), 19 (3), 19 (4), and 17. In the previous section we saw the PP should not be used to legitimately ban GM crops as a class. Article 17 of the CBD only addresses the facilitation of exchange of information. But what about the other three sections of the CBD: could they be used to justify a ban on all GM crops?

Article 8 (g) of the CBD requires that contracting parties shall

> "[e]stablish or maintain means to regulate, manage or control the risks associated with the use and release of living modified organisms resulting from biotechnology which are likely to have adverse environmental impacts that could affect the conservation and sustainable use of biological diversity, taking also into account the risks to human health";

Article 19 (3) of the CBD requires

> "The Parties shall consider the need for and modalities of a protocol setting out appropriate procedures, including, in particular, advance informed agreement, in the field of the safe transfer, handling and use of any living modified organism resulting from biotechnology that may have adverse effect on the conservation and sustainable use of biological diversity";

and Article 19 (4) of the CBD, however, only operates through Article 19(3) (Glowka et al. 1994: 97; CBD 2000). The language in Articles 8 (g) and 19 (3) of the CBD parallels that in Articles 1 and 4 of the Protocol, and the same rationale applies to why it would be inappropriate to use them to ban GM crops in toto.

A counterargument could be made that the appropriate test to determine whether a GMO should be subject to the Protocol's requirements would be to evaluate whether it may have *any* — and not just *aggregate* — adverse impact on the environment, conservation, sustainable use and human health. However, as the *any* in Article 19(3) of the CBD indicates, its negotiators seem to have been cognizant of that word's significance. Notably, *any* appears 43 times in the Protocol (and 66 times in the Convention).

8. Conclusion

The precautionary principle has often been invoked to justify a prohibition on GM crops (e.g., FOE 1999a, 1999b). However, this justification is based upon a selective application of the principle to a limited set of consequences of such a policy. Specifically, the justification takes credit for the potential public health and environmental benefits of a ban on GM crops, but ignores any discredit for foregoing or delaying the worldwide benefits to public health and the environment that such a ban would probably cause.

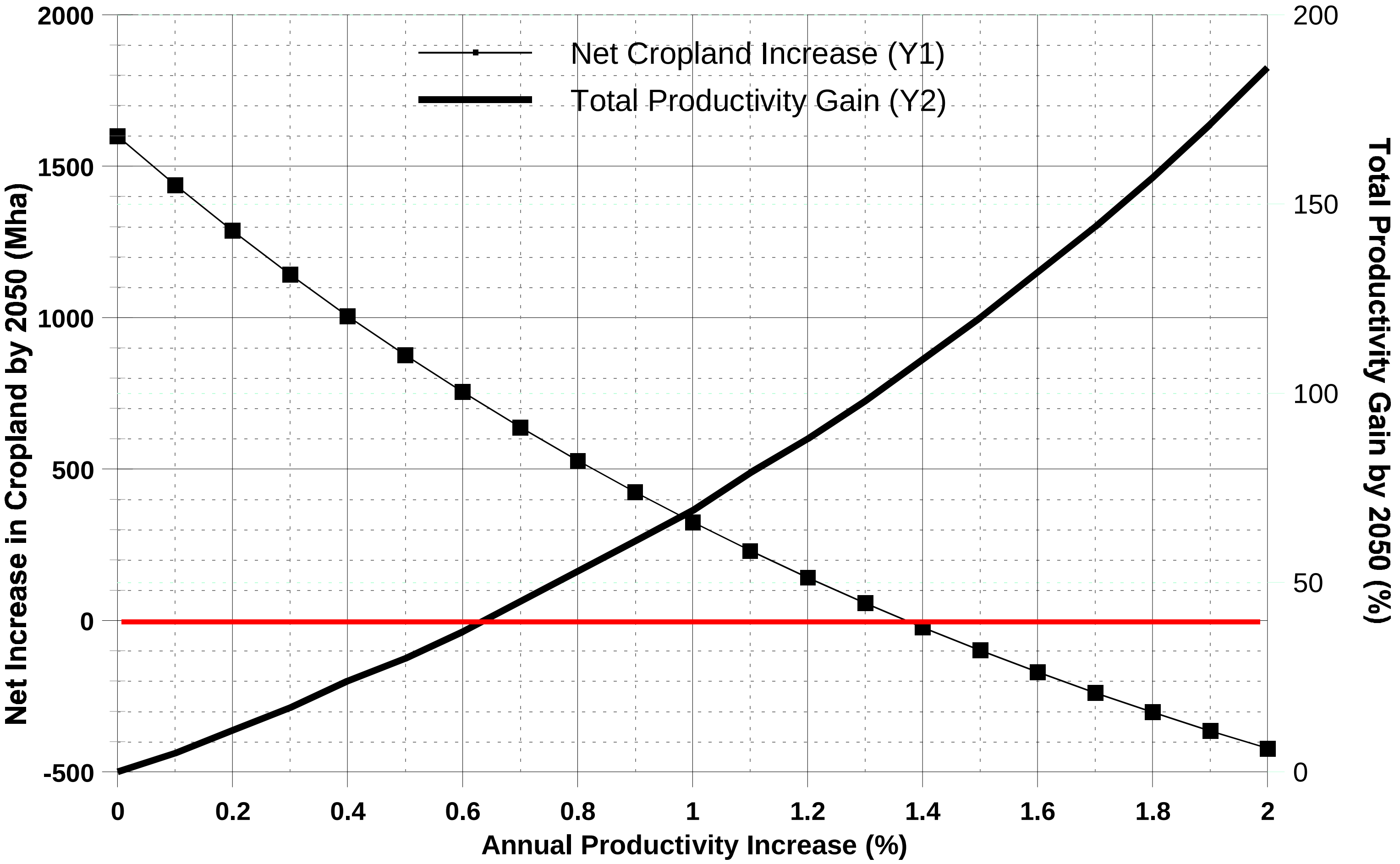
By comparison with conventional crops, GM crops would, in fact, increase the quantity and nutritional quality of food supplies. Thereby such crops would improve public health by reducing mortality and morbidity rates worldwide. In addition, cultivation of GM, rather than conventional, crops would, by increasing productivity, reduce the amount of land and water that would otherwise have to be diverted to mankind's needs. GM crops could also reduce the environmental damage from the use of synthetic fertilizers and pesticides, and from soil erosion. Thus GM crops would be more protective of habitat, biological diversity, water quality, and carbon stores and sinks than would conventional agriculture.

Hence a ban on GM crops — whether accomplished directly through the invocation of the precautionary principle or indirectly via application(s) of the Biosafety Protocol — is likely to aggravate threats to biodiversity and further increase the already considerable hurdles facing *in situ* conservation. Therefore a ban would be counterproductive and contravene the spirit and letter of the Convention on Biological Diversity. The precautionary principle — properly applied, with a more comprehensive 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 the crops.

In this context, a "reasonable" precaution is one whose public health benefits are not negated by the harm incurred due to reductions (or delays) in enhancing the quantity or quality of food. The public health costs of any reductions (or delays), which would make food more costly and reduce broader access to higher quality food at least for a period, would be disproportionately borne by the poorest and most vulnerable segments of society. Also the environmental gains flowing from a "reasonable" precaution should more than offset the environmental gains that would otherwise be obtained.

In summary, while it would be a mistake to go full steam ahead on GM crops, it would be at least as much a mistake to stop them in their tracks. The wisest policy would be to go as fast as possible while keeping a sharp lookout, and staying on the track to improvements in human and environmental well-being.

Figure 1: Net habitat loss to cropland vs. increase in agricultural productivity 1997 to 2050



Source: FAO (2000) per Goklany (1998a, 1999a).

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 <5 years (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 & cerebrovascular diseases	2.8 million deaths per year in HIC (1998) 9.7 million deaths per year in LIC/ MIC (1998) (includes those due to smoking)	moderate
Cancers	2.0 million deaths per year in HIC (1998) 5.2 million deaths per year in LIC/MIC (1998) (includes those due to smoking)	moderate

Note: HIC = high income countries; LIC = low income countries; MIC = mid income countries.
Sources: WHO 1999a 1999b, 1999c; FAO 1999b.

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