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ENVIRONMENTAL RISKS OF PESTICIDES VERSUS GENETIC ENGINEERING FOR AGRICULTURAL PEST CONTROL

(Accepted February 11, 2000)

ABSTRACT. Despite the application of 2.5 million tons of pesticides worldwide, more than 40% of all potential food production is lost to insect, weed, and plant pathogen pests prior to harvest. After harvest, an additional 20% of food is lost to another group of pests. The use of pesticides for pest control results in an estimated 26 million human poisonings, with 220,000 fatalities, annually worldwide. In the United States, the environmental and public health costs for the recommended use of pesticides total approximately $9 billion/yr. Thus, there is a need for alternative non-chemical pest controls, and genetic engineering (biotechnology) might help with this need. Disease and insect pest resistance to various pests has been slowly bred into crops for the past 12,000 years; current techniques in biotechnology now offer opportunities to further and more rapidly improve the non-chemical control of disease and insect pests of crops. However, relying on a single factor, like the *Bacillus thuringiensis* toxin that has been inserted into corn and a few other crops for insect control, leads to various environmental problems, including insect resistance and, in some cases, a threat to beneficial biological control insects and endangered insect species. A major environmental and economic cost associated with genetic engineering applications in agriculture relates to the use of herbicide resistant crops (HRC). In general, HRC technology results in increased herbicide use but no increase in crop yields. The heavy use of herbicides in HRC technology pollutes the environment and can lead to weed control costs for farmers that may be 2-fold greater than standard weed control costs. Therefore, pest control with both pesticides and biotechnology can be improved for effective, safe, economical pest control.

KEY WORDS: environment, genetic engineering, biotechnology, pesticides, agriculture, pest control, risks

1. INTRODUCTION

Synthetic pesticides have been applied to crops since 1945, and have been highly successful in both reducing crop losses to some pest insects, plant pathogens, and weeds, and in increasing crop yields (Pimentel, 1997). One estimate suggests that without pesticides, crop losses to pests might increase by 30%. Pesticides are also economically beneficial. One study estimated that pesticides return about $4 per dollar invested in pesticide applications (Pimentel et al., 1993). However, these benefits are not without some environmental and social costs of using pesticides (Pimentel and Greiner, 1997).

Journal of Agricultural and Environmental Ethics **12:** 279–303, 2000.
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Since 1970, genetic engineering technology has produced transgenic crops that, in some cases, can similarly reduce pest insect and plant pathogen problems in crops (Paoletti and Pimentel, 1996; McCullum et al., 1998). Approximately 34 genetically engineered crops have been approved for commercial use, but only a few of these have had a significant degree of pest insect and plant pathogen resistance included (Hammond and Fuchs, 1997).

Selection of breeding stock by farmers has occurred since the beginning of agriculture more than 12,000 years ago, and has increased the productivity of food and fiber crops in a variety of ways, including increasing the resistance and tolerance of crops to pest insects, plant pathogens, and weeds (Smith, 1995; Smith, 1989). Strategic breeding and selection, in addition to large inputs of fertilizers, irrigation, and pesticides, resulted in one of the highest achievements in agriculture, the Green Revolution (Smith, 1995). For example, corn yields increased nearly 4-fold, and new relatives of corn, including a perennial type, have been discovered (Smith, 1995; H. Iltis, personal communication, University of Wisconsin, 1998).

Genetic engineering techniques can move genes horizontally from one organism to another. For instance, Chinese scientists have spliced genes from a cold-tolerant fish into sugar beets, resulting in modified plants that can tolerate lower temperatures than normal sugar beets (Gene Exchange, 1998). These technologies have developed similar transgenic crops that are now becoming commercially available and are starting to compete with current crops.

The objective of this article is to assess the environmental risks of pesticides as compared to the risks associated with the application of genetic engineering and biotechnology in agricultural insect pest, plant pathogen, and weed control.

2. PESTICIDES AND PEST CONTROL

Approximately 70,000 species of pests exist in the world, but of these, only 10% are considered serious pests (Pimentel, 1997). Despite the use of more than 2.5 million tons of pesticides applied at an annual cost of $30 billion, pest insects, plant pathogens, and weeds continue to destroy more than 40% of the potential world food production (Oerke et al., 1994; Pimentel, 1997). Pre-harvest pest losses are approximately 15% for pest insects, 13% for disease, and about 12% for weeds. After harvest, another 20% of the food is lost to another group of pests (Pimentel, 1997).

In the United States, pre-harvest losses are slightly lower than the world average, about 37% of potential crop production (Pimentel, 1997). The losses are allocated as follows: 13% from insects, 12% from diseases, and 12% from weeds. These losses occur despite the heavy application of insecticides, fungicides, and herbicides. Approximately 3 kg of pesticide are applied per hectare in the US agricultural system (Pimentel et al., 1993).

What quantity of our crops are protected with pesticides? An estimated $8 billion is invested in pest control in the United States each year, saving approximately $32 billion in crops. If no pest controls – including pesticides, natural enemies, host-plant resistance and other non-chemical controls – were employed, the best estimate suggests that crop losses in the US would increase from 37% to 67%. Crop losses would then total about $100 billion per year. Therefore, pesticides are protecting about 30% of US crops. This estimate of benefits does not take into account the environmental and public health impacts of pesticides (discussed later).

Our opinion is that the same degree of pest control could be achieved with half the amount of the pesticides applied today (Pimentel et al., 1993). Estimates are that in order to achieve a 50% reduction in pesticide use, about $1 billion per year would have to be invested. However, the benefits resulting from reduced pesticide use and related reductions in environmental and public health problems would pay for this $1 billion investment, plus return several billion dollars in additional benefits (Pimentel et al., 1998).

The opportunities for improved pest management are apparent when we note that insecticide use in the United States grew more than 10-fold from 1945 to date, while losses to insects in US crops also increased from 7% in 1945 to 13% in 1997 (Pimentel et al., 1993; Pimentel et al., 1998). For some crops, like corn, losses to insects increased from 3.5% in 1945 to 12% in 1993, even with a more than 1000-fold increase in insecticide use (Pimentel et al., 1993). Corn production is now the largest user of insecticides in the United States. These increased insect problems (corn-rootworm complex) are due to the planting of more than half of the corn without crop rotations (Pimentel et al., 1993).

Public Health and Environmental Impacts of Pesticides

Human poisonings and their related illnesses are clearly the highest price paid for pesticide use. Worldwide, an estimated 26 million suffer from pesticide poisonings each year; approximately 3 million are poisoned seriously enough to be hospitalized and about 220,000 severely enough to prove fatal (UNEP, 1997).

The situation is especially serious in developing countries, even though these nations only utilize only 20% of the total pesticides applied in the world (Pimentel and Lehman, 1993). A high pesticide poisonings to deaths ratio occurs in developing countries, where there tend to be inadequate occupational safety standards, protective clothing, and washing facilities; insufficient enforcement of safety regulations; poor labeling of pesticides; illiteracy; and insufficient knowledge of pesticide hazards.

Additionally, average pesticide residue levels in food are often higher in developing countries than in developed nations. For example, a study in Egypt reported that a majority of assayed milk samples, when tested for fifteen different pesticides, contained residue levels in about 60–80% of the samples (Pimentel and Greiner, 1997).

About 35% of the foods purchased by American consumers, however, also have detectable levels of pesticide residues, generally considered acceptable amounts of pesticide contamination. However, 1–3% of these foods have pesticide residue levels that are above the legal tolerance level. Residue levels may be even higher than this because the analytical methods now employed in the US detect only about one-third of the more than 800 pesticides in use on crops (Pimentel and Hart, 1999).

Both the acute and chronic health effects of pesticides warrant attention and concern. While the acute toxicity of most pesticides is well documented, information on chronic human illnesses such as cancer is not as sound. Schottenfeld, of the University of Michigan (personal communication, 1991), estimates that fewer than 1% of the human cancer cases in the US are attributable to pesticide exposure. Since there are approximately 1.2 million new cancer cases annually, Schottenfeld’s assessment suggests that approximately 12,000 cases of cancer per year are due to pesticides (Pimentel and Hart, 1999).

There is also growing evidence of sterility in humans and various other animals, particularly in males, related to the presence of various chemicals and pesticides in the environment. Sperm counts in the United States and Europe have declined by about 50% and continue to decrease an additional 2% per year (Pimentel and Greiner, 1997). Some investigators question the decline in sperm counts and argue that variation between regions suggest that there may not have been a decline (Olsen et al., 1995; Fisch and Goluboff, 1996). Swan et al. (1997) examined all the studies claiming declines and those claiming no change in sperm counts worldwide, and concluded that the evidence supports a decline in sperm counts over time.

Further support for the evidence that sperm counts are declining is the fact that young male river otters in the lower Columbia River and male alligators in Florida’s Lake Apopka have smaller reproductive organs than males in unpolluted regions (Pimentel and Hart, 1999). Male rabbits treated with the pesticide carbosulfan also showed a significant decline in sperm concentration in the treated group (El-Zarkouny et al., 1999).

Although it is often difficult to determine the impact of individual pesticides and other chemicals, the chronic health problems associated with organophosphorus pesticides – which have largely replaced the banned organochlorines – are of particular concern. The malady Organophosphate Induced Delayed Polyneuropathy (OPIDP) is well-documented and is marked by irreversible neurological defects (Ecobichon et al., 1990). The deterioration of memory, moods, and the capacity for abstract thought have been observed in some cases, while other cases indicate that persistent neurotoxic effects may result even after the termination of an acute organophosphorus poisoning incident.

Many species – especially natural predators and parasites – control or help to control herbivorous pest populations in both natural and agroecosystems. Natural enemies play a major role in keeping the populations of many insect and mite pests under control, but these natural enemies can be adversely affected by pesticides. For example, bollworm, tobacco budworm, cotton aphid, spider mites, and cotton loopers have reached outbreak levels in cotton crops following the destruction of their natural enemies by pesticides; European red mites, red-banded leafroller, San Jose scale, oystershell scale, rosy apple aphid, wooly apple aphid, white apple leafhoppers, two-spotted spider mites, and apple rust mites have reached outbreak levels in apple crops for the same reason. Significant pest outbreaks have also occurred in other crops (Croft, 1990).

When outbreaks of secondary pests occur because their natural enemies are destroyed by pesticides, additional and sometimes more expensive pesticide treatments have to be made in an effort to sustain crop yields. This raises overall costs and contributes to pesticide-related problems. An estimated $520 million can be attributed to the cost of additional pesticide applications and increased crop losses, both of which result from the destruction of natural enemies by pesticides (Pimentel et al., 1998).

Wild birds are also destroyed by pesticides, and consequently make excellent “indicator species” of pollutant levels in the environment. Deleterious effects of pesticides on bird wildlife include death from direct exposure or secondary poisonings from consuming contaminated prey; reduced survival, growth, and reproductive rates from exposure to sublethal dosages; and habitat reduction through elimination of food sources and refuges. In the United States, approximately 3 kg of pesticide per hectare are applied to about 160 million ha of land per year. With such a large portion of the land area treated with heavy dosages of pesticide, one would expect the impact of pesticides on bird wildlife to be significant.

Many bird casualties caused by pesticides have been reported in the published literature. For instance, White et al. (1982) reported that 1200 Canada geese were killed in one wheat field that was sprayed with a 2:1 mixture of parathion and methyl parathion at a rate of 0.8 kg per ha. Carbofuran applied to alfalfa killed more than 5000 ducks and geese in 5 incidents, while the same chemical applied to vegetable crops killed 1400 ducks in a single incident (Flickinger et al., 1980, 1991). Carbofuran is estimated to kill 1–2 million birds each year (EPA, 1989). Another pesticide, diazinon, killed 700 of the wintering population of 2500 Atlantic Brant Geese after the pesticide was applied to three golf courses (Stone and Gradoni, 1985).

Several studies report that the use of herbicides in crop production results in the total elimination of the weeds that harbor some insects (R. Beiswenger, University of Wyoming, personal communication, 1990). This has led to subsequent reductions in the gray partridge in the United Kingdom and the common pheasant in the United States. In the case of the partridge, population levels have decreased more than 77% because partridge chicks (and pheasant chicks as well) depend on insects to supply them with the protein needed for their development and survival (R. Beiswenger, University of Wyoming, personal communication, 1990).

Frequently, the form of a pesticide influences its toxicity to wildlife. For example, treated seed and insecticide granules – including carbofuran, fensulfothion, fonofos, and phorate – are particularly toxic to birds when consumed. Many birds will ingest these granules either on purpose or by accident, thereby consuming the pesticide directly. Some recent research on managing this hazard has focused on the spraying of the pesticide treated area with a solution of a naturally occurring plant substance that is unpalatable to many types of birds (Chen, 1995). Another approach includes treating the granules with taste repellents before field application (Mastrota and Mench, 1995). Despite these measures, though, estimates suggest that 0.23–1.5 birds per ha are killed by pesticides in Canada; in the United States, about 0.25–8.9 birds per ha per year are estimated to die as a result of pesticide exposure (Mineau, 1988).

Although the gross economic values for wildlife are not available, expenditures involving wildlife are one measure of its monetary value. Non-consumptive users of wildlife spent an estimated $14.3 billion in 1985 (USFWS, 1988). Bird watchers in the US spend an estimated $600 million annually on their sport, and an additional $500 million on birdseed – a total of $1.1 billion (USFWS, 1988). The money spent by bird hunters to harvest

5 million game birds is about $1.1 billion annually, or approximately $216 per bird (USFWS, 1988). In addition, estimates of the value of all types of birds ranged from $0.40 to more than $800 per bird. The $0.40 per bird was based on the costs of bird-watching and the $800 per bird was based on the replacement costs of the affected species (Walgenbach, 1979; Tinney, 1982; Dobbins, 1986; James, 1995).

If it is assumed that the damage pesticides inflict on birds occur primarily on the 160 million hectares of cropland that receive most of the pesticide, and the bird population is estimated to be 4.2 birds per hectare of cropland (Blew, 1990), then 672 million birds are directly exposed to pesticides. If it is conservatively estimated that only 10% of the bird population is killed, then the total number of birds killed annually as a result of direct pesticide exposure is 67 million. Note that this estimate is at the low end of the range of 0.25 to 8.9 birds per ha killed annually by pesticides mentioned earlier in this section. Also, this is considered a conservative estimate because secondary losses to pesticide-related reductions in invertebrate prey poisonings were not included in the assessment. Assuming that the average value of a bird is $30, then an estimated $2 billion worth of birds are destroyed annually.

Pesticides have many other effects on the environment as well, including mammal, fish, and bee kills, surface and ground water contamination, soil and air contamination, and residue contamination of animal and crop products (Pimentel et al., 1998). The environmental effects of pesticide use in the United States total more than $9 billion each year.

3. GENETIC ENGINEERING

Benefits of Genetic Engineering in Pest Control

Many crops have been genetically modified to include resistance to insects, resistance to plant pathogens (including viruses) and herbicides, and for improved features such as slow ripening, higher nutritional status, seedless fruit, and increased sweetness. Up to 34 new genetically engineered crops have been approved to enter the market (Hammond and Fuchs, 1997).

Since 1986, more than 2000 field trials have led to the release of transgenic plants around the world (Krattinger and Rosemarin, 1994; Paoletti and Pimentel, 1996). In 1998, 27.8 million ha of engineered crops were planted in countries such as the United States, Argentina, Canada, and Australia. The US alone contains 74% of the modified cropland planted. Globally, 19.8% of this area has been planted with herbicide tolerant crops, 7.7% with insect resistant crops, and 0.3% with insect and herbicide resistant crops. Five crops – soybean, corn, cotton, canola, and potato – cover the largest acreage of engineered crops (James, 1998; Moff, 1998).

Disease Resistance in Crops

The crops currently on the market that have been engineered for resistance to plant pathogens are listed in Table I. Disease resistant engineered crops have some potential advantages because this reduces the use of fungicides.

However, the large-scale cultivation of plants expressing viral and bacterial genes might lead to some adverse ecological consequences. The most significant risk is the potential for gene transfer of disease resistance from cultivated crops to weed relatives. For example, it has been postulated that a virus-resistant squash could transfer its newly acquired virus-resistance genes to wild squash (*Cucurbita pepo*), which is native to the southern US If the virus-resistance genes spread, newly disease-resistant weed squash could become a hardier, more abundant weed. Moreover, because the US is the origin for squash, changes in the genetic make-up of wild squash could conceivably lessen its value to squash breeders. The US Department of Agriculture argues that viruses do not appear to infect wild squash, basing this conclusion largely on a survey of only 14 wild squash plants in which no viral infection was detected (Goldburg, 1995).

Another area of concern is the production of virus-resistant sugar beets, where there a similar exchange of genes between cultivated and weed populations of beet (*Beta vulgaris L.*) is likely, since production areas containing wild and/or weed beet populations are in the same region. Genetic exchange could take place by wind pollination, biotic pollination, or the common gynoniecy of wild beets (Boutin et al., 1987; Cuguen, 1994). A genetic introgression from seed beet to weed beet populations has already been observed in Europe (Santoni and Berville, 1992).

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

Virus-resistant crops may also lead to the creation of new viruses through an exchange of genetic material or recombination between RNA virus genomes. Recombination between RNA virus genomes requires infection of the same host cell with two or more viruses. Several authors

TABLE I

Plants genetically-engineered for virus resistance that have been approved for field tests in the United States from 1987 to July 1995 (Krimsky and Wrubel, 1996; McCullum et al., 1998)

Crop	Disease(s)	Reseach organization
Alfalfa	Alfalfa mosaic virus Tobacco mosaic virus (TMV) Cucumber mosaic virus (CMV)	Pioneer Hi-Bred
Barley	Barley yellow dwarf virus (BYDV)	USDA
Beets	Beet necrotic yellow vein virus	Betaseed
Cantelope and/or squash	CMV, papaya ringspot virus (PRV) Zucchini yellow mosaic virus (ZYMV) Watermelon mosaic virus II (WMVII)	UpJohn
	CMV	Harris Moran Seed
	ZYMV	Michigan State University
	ZYMV	Rogers NK Seed
	Soybean mosaic virus (SMV)	Cornell University
	SMV, CMV	New York State Experiment Station
Corn	Maize dwarf mosaic virus (MDMV) Maize chlorotic mottle virus (MCMV) Maize chlorotic dwarf virus (MCDV)	Pioneer Hi-Bred
	MDMV	Northup King
	MDMV	DeKalb
	MDMV	Rogers NK Seed
Cucumbers	CMV	New York State Experiment Station
Lettuce	Tomato spotted wilt virus (TSWV)	UpJohn
Papayas	PRV	University of Hawaii
Peanuts	TSWV	Agracetus
Plum trees	PRV, plum pox virus	USDA
Potatoes	Potato leaf roll virus (PLRV) Potato virus X (PVX) Potato virus Y (PVY)	Monsanto
	PLRV, PVY, late blight of potatoes	Frito-Lay
	PLRV	Calgene
	PLRV, PRY	University of Idaho
	PLRV, PVY	USDA
	PYV	Oregon State University
Soybeans	SMV	Pioneer Hi-Bred
Tobacco	ALMV, tobacco etch virus (TEV) Tobacco vein mottling virus	
	TEV, PVY	University of Florida
	TEV, PVY	North Carolina State University
	TMV	Oklahoma State University
	TEV	USDA
Tomatoes	TMV, tomato mosaic virus (TMV) CMV, tomato yellow leafcurl virus	Monsanto
	TMV, ToMV	UpJohn
	ToMV	Rogers NK Seed
	CMV	PetoSeed
	CVM	Asgrow
	CMV	Harris Moran Seeds
	CMV	New York State Experiment Station
	CMV	USDA

have pointed out that recombination could also occur in genetically-engineered plants expressing viral sequences of infection with a single virus, and that large-scale cultivation of such crops could lead to increased possibilities of combinations (Hull, 1990; Palukaitis, 1991; de Zoeten, 1991; Tepfer, 1993). It has recently been shown that RNA transcribed from a transgene can recombine with an infecting virus to produce highly virulent new viruses (Greene and Allison, 1994).

Assessment of Transgenic Virus-resistant Potatoes in Mexico

An in-depth assessment of potential socioeconomic implications related to the introduction of some genetically-modified varieties of virus-resistant potatoes (PVY, PVX, PlRV) in Mexico underscores the importance of biotechnology. This type of genetic modification could prove especially beneficial to large scale farmers, but only marginally beneficial to small scale farmers, because most small farmers use red potato varieties that are not considered suitable for biotechnology transformation. In addition, 77% of the seeds that small farmers use come from other farmers, not from the seed producers that could sell the new resistant varieties (Quaim, 1998).

The mycoplasma and virus diseases in Mexico are not currently controlled with pesticides, and rank second and third in economic damage. The major pest, the fungus *Phytophtora infestans*, ranks first in economic damage and requires, in some cases, up to 30 fungicide applications (Parga and Flores, 1995). Thus, the interesting new genetically altered varieties of potatoes appear to be of little benefit to crop production for small farmers.

Herbicide-Resistant Crops (HRCs)

Several engineered crops that include herbicide-resistance are commercially available, and 13 other key crops in the world are ready for field trials (Table II). In addition, some crops (e.g., corn) are being engineered to contain both herbicide (Glyphosate) and biotic insecticide-resistance (BT d-endotoxin) (Gene Exchange, 1997).

The resistance of crops to target herbicides would, in practice, result in farmers applying large quantities of herbicides (Paoletti and Pimentel, 1996). In addition, costs for this new technology of HRCs are about 2-times higher in corn than the recommended herbicide use and cultivation weed control program (Pimentel and Ali, 1998). Herbicide use on herbicide-tolerant soybeans was 2 to 5 times higher than in conventional soybean production (Benbrook, 1999).

Integrated pest management (IPM) could benefit from some HRCs, if alternative non-chemical methods can be applied first to control weeds and the target herbicide could be used later, only when and where the economic

TABLE II

Herbicide-resistant crops (HRCs) approved for field tests in the United States from 1987 to July 1995 (adapted from: Krimsky and Wrubel, 1996; Gene Exchange, 1997; McCullum et al., 1998)

Crop	Herbicide	Research organization
Alfalfa	Glyphosate	Northrup King
Barley	Glufosinate/Bialaphos	USDA
Canola (oilseed rape)	Glufosinate/Bialaphos	University of Idaho
		Hoechst-Roussel/AgrEvo
	Glyphosate	InterMountain Canola
		Monsanto
Corn	Glufosinate/Bialaphos	Hoechst-Roussel/AgrEvo
		ICI
		UpJohn
		Cargill
		DeKalb
		Holdens
		Pioneer Hi-Bred
		Asgrow
		Great Lakes Hybrids
		Ciba-Geigy
		Genetic Enterprises
	Glyphosate	Monsanto
		DeKalb
	Sulfonylurea	Pioneer Hi-Bred
		DuPont
	Imidazolinone	American Cyanamid
Cotton	Glyphosate	Monsanto
		Dairyland Seeds
		Northrup King
	Bromoxynil	Calgene
		Monsanto
		Rhone Poulenc
	Sulfonylurea	DuPont
		Delta and Pine Land
	Imidazolinone	Phytogen
Peanuts	Glufosinate/Bialaphos	University of Florida
Potatoes	Bromoxynil	University of Idaho
		USDA
	2,4-D	USDA
	Glyphosate	Monsanto
	Imidazolinone	American Cyanamid
Rice	Glufosinate/Bialaphos	Louisiana State University
Soybeans	Glyphosate	Monsanto
	Glyphosate	UpJohn
		Pioneer Hi-Bred
		Northrup King
		Agri-Pro
	Glufosinate/Bialaphos	UpJohn
		Hoechst/AgroEvo
	Sulfonylurea	DuPont
Sugar Beets	Glufosinate/Bialaphos	Hoechst-Roussel
	Glyphosate	American Crystal Sugar
Tobacco	Sulfonylurea	American Cyanmid
Tomatoes	Glyphosate	Monsanto
	Glufosinate/Bialaphos	Canners Seed
Wheat	Glufosinate/Bialaphos	AgrEvo

threshold of weeds is surpassed (Krimsky and Wrubel, 1996). Generally, though, the use of herbicide resistant crops will lead to increased use of herbicides and environmental and economic problems (McCullum et al. 1998; Pimentel and Ali, 1998; Altieri, 1998).

Most HRCs were developed for Western agriculture (Krimsky and Wrubel, 1996). One innovation that would help developing countries is the control of parasitic weeds – such as *Orobanche* and *Stringa,* both of which severely reduce grain yields. Trials on broomrape have demonstrated that HRCs can produce at least double the yields as compared to the control crops. However, the authors observed that this technology could only be used with weeds that are not potentially interbreeding with wild weed relatives (Joel et al., 1995). For example, in Northern African countries, most crops, such as sorghum, wheat, and canola (oilseed rape), have wild weed relatives, thereby increasing the risk that genes from the herbicide-resistant crop varieties could be transferred to wild weed relatives (Mikkelsen et al., 1996; BSTID, 1996).

The risk of herbicide-resistant genes from a transgenic crop variety being transferred to weed relatives has been demonstrated for canola (oilseed rape) and sugar beet. Mikkelsen et al. (1996) and Brown and Brown (1996) have shown that herbicide-resistant genes from transgenic canola move quickly into weed relatives. Boudry et al. (1994) also revealed gene flow between cultivated sugar beets and wild/weed beet populations.

Repeated use of herbicides in the same area creates problems of weed herbicide resistance (Wrubel and Gressel, 1994). For instance, if glyphosate is used with HRCs crops on about 70 million ha, this might accelerate pressure on weeds to evolve herbicide resistant biotypes (Gressel, 1992; Krimsky and Wrubel, 1996). Sulfonylureas and imidazolinones in HRCs are particularly prone to rapid evolution of resistant weeds (LeBaron and McFarland, 1990; Wrubel and Gressel, 1994). Extensive adoption of HRCs will increase the hectarage and surface treated, thereby exacerbating the resistance problems and environmental pollution problems (Krimsky and Wrubel, 1996).

Bromoxynil has been targeted in herbicide resistant cotton by Calgene and Monsanto (Table II). This herbicide has been used on winter cereals, cotton, corn, sugarbeets, and onions to control broad leaf weeds. Drift of bromoxynil has been observed to damage nearby grapes, cherries, alfalfa, and roses (Al Khatib et al., 1992). In addition, leguminous plants can be sensitive to this herbicide (Abd Alla and Omar, 1993), and potatoes can be damaged by it. Herbicide residues above the accepted standards have been detected in soil and groundwater (Miller et al., 1995), and as drift fallout (Waite et al., 1995). Rodents demonstrate some mutagenic responses to bromoxynil (Rogers and Parkes, 1995). Some beneficial beetles show reduced survival and egg production at recommended dosages of bromoxynil (Samsoe-Peterson, 1995). Crustaceans (*Daphnia magna*) are reported to be negatively affected by this herbicide (Buhl et al., 1993).

Toxicity of Herbicides and Herbicide Resistant Crops

Toxic effects of herbicides to humans and animals also have been reported (Cox, 1996). For example, the Basta surfactant (sodium polyoxyethylene alklether sulfate) has been shown to have strong vasodialatative effects in humans and cardiostimulative effects in rats (Koyama et al., 1997). Treated mice embryos exhibited specific morphological defects (Watanabe and Iwase, 1996).

Most HRCs have been engineered for Glyphosate resistance (James, 1998). Although adverse effects of herbicide-resistant soybeans have not been observed when fed to animals such as cows, chickens, and catfish, genotoxic effects have been demonstrated on other non-target organisms (Cox, 1995a,b). Earthworms have been shown to be severely injured by the glyphosate herbicide at 2.5–10.1/ha. (Reanova et al., 1996). For example, *Allolobophora caliginosa*, the most common earthworm in European, North American, and New Zealand fields, is killed by this herbicide (Mohamed et al., 1995; Springett and Gray, 1992). In addition, aquatic organisms, including fish, can be severely injured or killed when exposed to glyphosphate (Henry et al., 1994; WHO, 1994). The beneficial nematode, *Steinerema feltiae*, a useful biological control organism, is reduced by 19–30% by the use of glyphosphate (Forschler et al., 1990).

There are also unknown health risks associated with the use of low doses of herbicides (Wilkinson, 1990). Due to the common research focus on cancer risk, little research has been focused on neurological, immunological, developmental, and reproductive effects of herbicide exposures (Krimsky and Wrubel, 1996). Much of this problem is due to the fact that scientists may lack the methodologies and/or the diagnostic tests necessary to properly evaluate the risks caused by exposure to many toxic chemicals, including herbicides.

While industry often stresses the desirable characteristics of their HRCS, environmental and agricultural groups, and other scientists, have indicated the risks (Pimentel et al, 1998; McCullum et al., 1998). Feeding experiments have shown that cows fed transgenic glyphosate-resistant soybeans had a statistically significant difference in daily milk-fat production as compared to control groups (Hammond et al., 1996).

Economic Impacts of Herbicide Resistant Crops

The herbicides for which HRCs are being designed are more expensive than many of the herbicides they are intended to replace (see Table I). While some analysts project that switching to bromoxynil for broadleaf weed control in cotton could result in savings of $37 million each year from reductions in herbicide purchases, few other economic product evaluations demonstrate cost savings with the use of HRCS (Krimsky and Wrubel, 1996). Furthermore, recent problems with use of glyphosate-resistant cotton in the Mississippi Delta region – crop losses resulting in up to $500,000 of this year's cotton crop – suggest that this technology needs to be further developed before some farmers will reap economic benefits (Fox, 1997). In addition, a recent study of herbicide resistant corn suggests that the costs of weed control might be about 2-times more expensive than normal herbicide and cultivation weed control in corn (Pimentel and Ali, 1998). Farmers were also reported to use 2–5 more herbicide per hectare on herbicide resistant soybeans than in conventional soybean production (Benbrook, 1999).

While some scientists suggest that use of HRCs will cause a shift to fewer broad-spectrum herbicides (Hayenga et al., 1992), most scientists conclude that the use of HRCs will actually increase herbicide use (Goldburg et al., 1990; Rissler and Mellon, 1993; Paoletti and Pimentel, 1995; Paoletti and Pimentel, 1996; Pimentel and Ali, 1998).

Bacillus Thuringiensis (BT) for Insect Control

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

Some trials with corn demonstrate a high level of efficacy in controlling corn borers (Steffey, 1995). Corn engineered with BT-endotoxin has the potential to reduce corn borer damage by 5–15% over 28 million hectares in the US, with a potential economic benefit of $50 million annually (Steffey, 1995). Some suggest that corn engineered with BT toxin will increase yields by 7% over similar varieties (Moff, 1998; Rice and Pilcher, 1998; James, 1998). Trials in Italy demonstrated that engineered corn increased yields 2–28%, but has a 1.8% higher grain moisture level at harvest (Verderio et al., 1998). However, it is too early to tell if all these benefits will be realized consistently. Potential negative environmental

TABLE III

Transgenic insect resistant crops containing BT d-endotoxins. Approved field tests in United States from 1987 to July 1995 (Krimsky and Wrubel, 1996; Gene Exchange, 1996)

Crop	Research organization
Alfalfa	Mycogen
Apples	Dry Creek University of California
Corn	Asgrow Cargill Ciba-Geigy Dow Genetic Enterprises Holdens Hunt-Wesson Monsanto Mycogen NC+Hybrids Nortrup King Pioneer Hi-Bred Rogers NK Seed
Cotton	Calgene Delta and Pineland Jacob & Hartz Monsanto Mycogen Northrup King
Cranberry	University of Wisconsin
Eggplant	Rutgers University
Poplar	University of Wisconsin
Potatoes	USDA Calgene Frito-Lay Michigan State University Monsanto Montana State University New Mexico State University University of Idaho
Rice	Louisiana State University
Spruce	University of Wisconsin
Tobacco	Auburn University Calgene Ciba-Geigy EPA Mycogen North Carolina State University Roham & Haas
Tomatoes	Campbell EPA Monsanto Ohio State University PetoSeeds Rogers NK Seeds
Walnuts	University of California, Davis USDA

effects also exist because the pollen of engineered plants contains BT, which is toxic to bees, beneficial predators, and endangered butterflies like the Karka Blue and Monarch Butterflies (Losey et al., 1999).

Cotton was the first crop plant engineered with the BT d-endotoxin. Caterpillar pests, including the cotton bollworm and budworm, cost US farmers about $171 million/year as measured in yield losses and insecticide costs (Head, 1991). Benedict et al. (1992) predict that the widespread use of BT-cotton could reduce insecticide use and thereby reduce costs by as much as 50% to 90%, saving farmers $86 to $186 million/year.

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

Effects of BT d-endotoxin on Non-target Organisms

It has also been demonstrated that predators, such as the lacewing larvae (*Crysoperla carnea*) that feed on corn borers (*Ostrinia nubilalis*), grown on engineered BT-corn have consistently higher mortality rates when compared to specimens fed with non-engineered corn borers. In addition, the treated larvae need three more days to reach adulthood than lacewings fed on prey from non-BT corn (Hilbeck et al., 1998).

Single-Gene Changes and Increased Pathogenicity

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

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

Threats from Modified Native Species

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

4. DISCUSSION

Both pesticides and biotechnology have definite advantages in reducing crop losses to pests. At present, pesticides are used more widely than biotechnology, and thus are playing a greater role in protecting world food supplies. In terms of environmental and public health impacts, pesticides probably have a greater negative impact at present because of their more widespread use.

Genetically engineering crops for resistance to insect pests and plant pathogens could, in most cases, be environmentally beneficial, because these more resistant crops could allow a reduction in the use of hazardous insecticides and fungicides in crop production. In time, there may also be economic benefits to farmers who use genetically engineered crops; this will depend, though, on the prices charged by the biotechnology firms for these modified, transgenic crops.

There are, however, some environmental problems associated with the use of genetically engineered crops in agriculture, as discussed above. A major environmental and economic concern associated with genetically engineered crops is the development of herbicide-resistant-crops (HRCs). Although in rare instances HRCs may result in a beneficial reduction of toxic herbicide use, it is more likely that the use of herbicide resistant crops will increase herbicide use and environmental pollution. In addition, farmers will suffer because of the high costs of employing herbicide resistant crops – in some instances, weed control with HRCs may increase weed control costs for the farmer 2-fold (Pimentel and Ali, 1998).

More than 40% of the research by biotechnology firms is focused on the development of herbicide resistant crops. This is not surprising, because most of the biotechnology firms are also chemical companies who stand to profit if herbicide resistance in crops result in greater pesticide sales (Paoletti and Pimentel, 1996). Theoretically, the acceptance and use of engineered plants in sustainable and integrated agriculture should consistently reduce current use of pesticides, but this is not the current trend. In addition, most products and new technologies are designed for Western agriculture systems, and are not for poor farmers in developing countries (Altieri, 1998; Moff, 1998). For instance, if terminator genes enter into the seed market, there will be no possibility of traditional and small farmers using their plants to produce their seeds (Berlan and Lewontin, 1998).

Thus, genetic engineering could promote improvements for the environment; however, the current products – especially the herbicide-resistant crops and the BT-resistant crops – have some serious environmental impacts.

REFERENCES

Abd Alla, M. H. and S. A. Omar, "Herbicides Effects on Nodulation, Growth, and Nitrogen yield of faba bean Introduced by Indigenous Rhizobium Leguminosarum," *Zentralblatt fur Mikrobiologie* 148(8) (1993), 593–597.

Alexander, M., “Ecological Consequences of Reducing the Uncertainties,” *Issues in Science and Technology* 1(3) (1985), 57–68.

Al Khatib, K., R. Parker, and E. P. Fuerst, “Sweet Cherry Response to Simulated Drift from Selected Herbicides,” *Proceedings Western Society of Weed Society*, Vol. 45 (Salt Lake City, Utah, 1992), pp. 2–27.

Altieri, M. A., “The Environmental Risks of Transgenic Crops: An Agroecological Assessment,” *Fifth Annual ESSD Conference Proceedings* (World Bank, Washington DC, 1998).

Bartlett, A. C., “Resistance of the Pink Bollworm to BT Transgenic Cotton,” in D. A. Richter and J. Amour (eds.), *Proceedings Beltwide Cotton Conference, National Cotton Council of America* (National Cotton Council of America, Memphis, TN, 1995), p. 766.

Benbrook, C., *Evidence of the Magnitude and Consequences of the Roundup Ready Soybean Yield Drag from University-based Varietal Trials in 1998* (Ag BioTech InfoNet Technical Paper Number 1, July 13, 1999), http://www.biotech-info.net/RR_yield_drag_98.pdf

Benedict, J. H., D. R. Ring, E. S. Sachs, D. W. Altman, R. R. DeSpain, T. B. Stone, and J. R. Sims, “Influence of Transgenic BT Cottons on Tobacco Budworm and Bollworm Behavior Survival, and Plant Injury,” in J. Herber and D. A. Richter (eds.), *Proceedings Beltwide Cotton Council* (National Cotton Council, Memphis, TN, 1992), pp. 891–895.

Berlan J. P. and R. C. Lewontin, “La menace du complexe genetico-industriel,” *Le Monde Diplomatique* (22 Dec., 1998).

Blew, J. H., “Breeding Bird Census 92 Conventional Cash Crops Farm,” *Journal of Field Ornithology* 61(suppl.) (1990), 80–81.

BSTID (Board on Science and Technology for International Development), *Lost Crops of Africa*, Vol. 1 (National Academic Press, Washington DC, 1996), pp. 1–383.

Bommineni, V. R., P. P. Jauhar, and T. S. Peterson, “Transgenic Durum Wheat by Microprojectile Bombardment of Isolated Scutella,” *Journal of Heredity* 88(6) (1997), 474–481.

Boudry, P., K. Broomberg, P. Saumitou-Laprade, M. Morchen, J. Cuegen, and H. Van Dijk, “Gene Escape in Transgenic Sugar Beet: What Can be Learned from Molecular Studies of Weed Beet Populations?” *Proceedings of the 3rd International Symposium on the Biosafety Results of Field Tests of Genetically-Modified Plants and Microorganisms*, Monterey, California, November 13–16 (The University of California, Division of Agriculture and Natural Resources, Oakland, CA, 1994), pp. 75–83.

Boutin, V., G. Pannenbecker, W. Ecke, G. Schewe, P. Saumitou-Laprade, R. Jean, P. Vernet, and G. Michealis, “Cytoplasmic Male Sterility and Nuclear Restorer Genes in a Natural Population of Beta Maritima: Genetical and Molecular Aspects,” *Theor. Appl. Genet.* 73 (1987), 625–629.

Brown, J. and A. P. Brown, “Gene Transfer Between Canola (*Brassica napus* and *B. campestris*) and Related Weed Species,” *Annals of Applied Biology* 129(3) (1996), 513–522.

Buhl, K. J., S. J. Hamilton, and J. C. Schmulbach, “Chronic Toxicity of Bromoxynil Formulation Buctril to Daphnia Magna Exposed Continuously and Intermittently,” *Archives Env. Cont. And Toxicology* 25(2) (1993), 152–159.

Chen, C., “Flavoring Against Fowl,” *Cornell Countryman* (April/May, 1995), 24.

Cox, C., “Glyphosate, Part 1: Toxicology,” *Journal of Pesticide Reform* 15(3) (1995a), 14–20.

Cox, C., “Glyphosate, Part 2: Toxicology,” *Journal of Pesticide Reform* 15(4) (1995b), 14–20.

Cox, C., "Herbicide Factsheet: Glufosinate," *Journal of Pesticide Reform* 16(4) (1996), 15–19.

Croft, B. A., *Arthropod Biological Control Agents and Pesticides* (J. Wiley & Sons, New York, 1990).

Cuguen, B., R. Wattier, L. Saumitou, D. Forcioli, M. Morchen, H. Van Dilk, and P. Vernet, "Gynodiecy and Mitochondrial DNA Polymorphism in Natural Populations of Beta vulgaris ssp. maritima," *Geneti. Sci. Evol.* 26 (1994), 87–101.

de Zoeten, G. A., "Risk Assessment: Do We Let History Repeat Itself," *Phytopathology* 81 (1991), 585–586.

Dobbins, J., "Resources Damage Assessment of the T/V Puerto Rican Oil Spill Incident," *Report to NOAA* (Sanctuary Program Division, Washington, DC, 1986).

Ecobichon, D. J., J. E. Davies, J. Doull, M. Ehrlich, R. Joy, D. McMillan, R. MacPhail, L. W. Reiter, W. Slikker, and H. Tilson, "Neurotoxic Effects of Pesticides," in C. F. Wilkinson and S. R. Baker (eds.), *The Effect of Pesticides on Human Health* (Princeton Scientific, Princeton, NJ, 1990), pp. 131–199.

Elton, C. S., *The Ecology of Invasions by Animals and Plants* (Methuen, London, 1958).

El-Zarkouny, S. A., M. A. Ayoub, M. H. G. Ishak, F. D. El Nouty, G. A. Hassan, R. Abo El Ezz Zahraa, and M. H. Salem, "Effect of Carbosulfan Pesticide and Selenium on Some Semen Characteristics and Serum Testosterone in Male Rabbits," *International Journal of Environmental Health Research* 9(2) (1999), 117–124.

EPA, *Carbofuran: A Special Review Technical Support Document* (US Environmental Protection Agency, Office of Pesticides and Toxic Substances, Washington, DC, 1989).

Fernandez-Cuartero, B., J. Burgyan, M. A. Aranda, K. Salanki, E. Moriones, and F. Garcia-Arenal, "Increase of the Relative Fitness of a Plant Virus RNA Associated with Its Recombinant Nature," *Virology* 203 (1994), 373–377.

Fisch, H. and E. T. Goluboff, "Geographic Variations in Sperm Counts: A Potential Cause of Bias in Studies of Sperm Quality," *Fertility and Sterility* 65(5) (1996), 1044–1046.

Flickinger, E. L., K. A. King, W. F. Stout, and M. M. Mohn, "Wildlife Hazards from Furadan 3G Application to Rice in Texas," *Journal of Wildlife Management* 44 (1980), 190–197.

Flickinger, E. L., G. Juenger, T. J. Roffe, M. R. Smith, and R. J. Irwin, "Poisoning of Canada Geese in Texas by Parathion Sprayed for Control of Russian Wheat Aphid," *Journal of Wildlife Diseases* 27 (1991), 265–268.

Forschler, R. T., J. N. All, and W. A. Gardner, "Steinermafeltiae Activity and Infectivity in Response to Herbicide Exposure in Aqueous and Soil Environments," *J. Invertebrate Pathology* 55(3) (1990), 375–379.

Fox, J. L., "Farmers Say Monsanto's Engineered Cotton Drops Bolls," *Nature BioTechnology* 15 (1997), 1233.

Gene Exchange (Union of Concerned Scientists, Washington, DC, Fall 1997), pp. 6–8.

Gene Exchange (UCS [Union of Concerned Scientists], Summer 1998), www.ucsusa.org

Goldburg, R., J. Rissler, H. Shand, and C. Hassebrook, *Biotechnology's Bitter Harvest. A Report of the Biotechnology Working Group* (1990).

Goldburg, R., "Pause at the Amber Light," *Ceres* 153 (1995), 21–26.

Goldburg, R. J. and G. Tjaden, "Are B.T.K. Plants Really Safe to Eat?" *BioTechnology* 8 (1990), 1011–1015.

Gonsalves, D., M. Fuchs, F. Klas, and P. Tennant, "Field Assessment of Risks When Using Transgenic Papayas, Cucurbits, and Tomatoes Expressing Viral Coat Protein Genes," *Proceedings of the 3rd International Symposium on the Biosafety Results of Field Tests of Genetically-Modified Plants and Microorganisms*, Monterey, California, November

13–16 (The University of California, Division of Agriculture and Natural Resources, Oakland, CA, 1994), pp. 117–127.

Greene, A. E. and R. F. Allison, “Recombination Between Viral RNA and Transgenic Plant Transcript,” *Science* 263 (1994), 1423–1425.

Greef, W. De, R. Delon, M. de Block, J. Leemans, and J. Botterman, “Evaluation of Herbicide Resistance in Transgenic Crops under Field Conditions,” *Bio/Technology* 7(1) (1989), 61–64.

Gressel J., *Genetically-Engineered Herbicide Resistant Crop – A Moral Imperative for World Food Production* (Agro-Food Industry. Hi Tech, Jonpaper, 1992), p. 15.

Hayenga, M. L., C. Thompson, C. Chase, and S. Kaaria, “Economic and Environmental Implications of Herbicide-Tolerant Corn and Processing Tomatoes,” *Journal of Soil and Water Conservation* 47 (1992), 411–417.

Hammond, B. G., J. L. Vicini, G. F. Hartnell, M. W. Naylor, C. D. Knight, E. H. Robinson, R. L. Fuchs, and S. R. Padgette, “The Feeding Value of Soybeans Fed to Rats, Chickens, Catfish, and Dairy Cattle Is Not Altered by Genetic Incorporation of Glyphosphate Tolerance,” *Journal of Nutrition* 126(3) (1996), 717–727.

Hammond B. G. and R. L. Fuchs, “Safety Evaluation for New Varieties of Food Crops Developed Through Biotechnology,” in J. A. Thomas (ed.), *Biotechnology and Safety Assessment* (Taylor & Francis, Washington DC, 1997), pp. 61–79.

Head, R. B., “Cotton Insect Losses,” *Proceedings of the National Cotton Council of America, 1991–1993*, Vol. 2 (Memphis, TN, 1991), pp. 655–660.

Heath, M. C., B. Valent, R. J. Howard, and F. G. Chumley, “Correlations Between Cytological Detected Plant-Fungal Interactions and Pathogenicity of Magnaporthe Grisea Toward Weeping Lovegrass,” *Phytopathology* 80(12) (1990), 1382–1386.

Henry, C. J., K. F. Higgins, and K. J. Buhl, “Acute Toxicity and Hazard Assessment of Rodeo, Spreader, and Chem-Trol to Aquatic Invertebrates,” *Activities of Environmental Contamination and Toxicology* 27(3) (1994), 392–399.

Hilbeck, A., M. Baumgartner, M. Fried-Padrout, and F. Bigler, “Effects of Transgenic Bacillus Thuringiensis Corn-Fed Prey on Mortality and Development time of immature *Chrysoperla carnea*,” *Environmental Entomology* 27 (1998), 480–487.

Hull, R., “The Use and Misuse of Viruses in Cloning and Expression in Plants,” in R. S. S. Frazer (ed.), *Recognition and Response in Plant-Virus Interactions*, NATO ASI, Vol. H41 (Springer-Verlag, Berlin and Heidelberg, 1990), pp. 443–457.

James C., “Global Review of Commercialized Transgenic Crops,” *ISAAA Briefs* (Cornell University, 8/1998).

James, P. C., “Internalizing Externalities: Granular Carbofuran Use on Rapeseed in Canada,” *Ecology and Economics* 13 (1995), 181–184.

Jepson, P. C., B. C. Croft, and G. E. Pratt, “Test Systems to Determine the Ecological Risks Posed by Toxin Release from Bacillus thuringiensis Genes in Crop Plants,” *Molecular Ecology* 3 (1994), 81–89.

Joel, D., M. Kleifeld, Y. Losner-Goshen, G. Hezlinger, and J. Gessler, “Transgenic Crops Against Parasites,” *Nature* 374 (1995), 220–221.

Koyama, K., K. Koyama, and K. Goto, “Cardiovascular Effects of a Herbicide Containing Glufosinate and a Surfactant: In Vitro and In Vivo Analyses in Rats,” *Toxicology and Applied Pharmacology* 145(2) (1997), 409–414.

Krattinger, A. F. and A. Rosemarin, *Biosafety for Sustainable Agriculture: Sharing Biotechnology Regulatory Experiences of the Western Hemisphere* (ISAAA, Ithaca, NY, 1994).

Krimsky, S. and R. P. Wrubel, *Agricultural Biotechnology and the Environment* (Univ. Illinois Press, Urbana, IL, 1996), 294 pp.

LeBaron H. M. and J. E. McFarland, "Resistance to Herbicides," *Chemtech* 20 (1990), 508–511.

Lindgren, P. B., N. J. Panopoulos, B. J. Staskawicz, and D. Dahlbeck, "Genes Required for Pathogenicity and Hypersensitivity Are Conserved and Interchangeable Among Pathovars of *Peudomanas syringae*," *Molecular & General Genetics* 211(3) (1988), 499–506.

Lindow, S. E., "Methods of Preventing Frost Injury Caused by Epiphytic Ice-Nucleation-Active Bacteria," *Plant Disease* 67 (1983), 327–333.

Losey, J., L. S. Rayor, and M. E. Carter, "Transgenic Pollen Harms Monarch Larvae," *Nature* 399 (1999), 214.

Mastrota, F. N. and J. A. Mench, "Evaluation of Taste Repellents with Northern Bobwhites for Deterring Ingestion of Granular Pesticides," *Environmental Toxicology and Chemistry* 14 (1995), 631–638.

McCullum C., Pimentel D., and M. G. Paoletti, "Genetic Engineering in Agriculture and the Environment: Risks and Benefits," in J.A. Thomas (ed.), *Biotechnology and Safety Assessment* (Taylor & Francis, Washington, DC, 1998), pp. 177–217.

Mikkelsen, T. R., B. Anderson, and R. B. Jorgensen, "The Risk of Crop Transgene Spread," *Nature* 380 (1996), 31.

Miller, J. J., B. C., Hill, C. Chang, and C. W. Lindwall, "Canadian Journal of Soil," *Science* 75(3) (1995), 349–356.

Mineau, P., "Avian Mortality in Agroecosystems. I. The Case Against Granular Insecticides in Canada," in M. P. Greaves, B. D. Smith, and P. W. Greig-smith (eds.), *Field Methods for the Study of Environmental Effects of Pesticides.* London: British Crop Protection Council, Monograph 40, Thornton Heath, London, 1988), pp. 3–12.

Mohamed, A.-I., G.-A. Nair, H.-H. Kassem, and M.-Nuruzzaman, "Impacts of Pesticides on the Survival and Body Mass of the Earthworm *Aporrectodea caliginosa (Annelida: Oligochaeta*)," *Acta Zoologica Fennicica* 196 (1995), 344–347.

Moff, A. S., "Toting up the Early Harvest of Transgenic Plants," *Science* 282 (1998), 2176–2178.

NAS, *Introduction of Recombinant DNA-Engineered Organisms into the Environment: Key Issues* (National Academy of Sciences, Washington, DC, 1987).

Oerke, E. C., H. W. Dehne, F. Schonbeck, and A. Weber, *Crop Production and Crop Protection: Estimated Losses in Major Food and Cash Crops* (Elsevier, Amsterdam, 1994).

Olsen, G. W., K. M. Bodner, J. M. Ramlow, C. E. Ross, and L. I. Lipshultz, "Have Sperm Counts been Reduced 50 Percent in 50 Years? A Statistical Model Revisited', *Fertility and Sterility* 63(4), 887–893.

Paoletti, M. G. and D. Pimentel, "The Environmental and Economic Costs of Herbicide Resistance and Host-Plant Resistance and Host-Plant Resistance to Plant Pathogens and Insects," *Technological Forecasting and Social Change* 50 (1995), 9–23.

Paoletti, M. G. and D. Pimentel, "Genetic Engineering in Agriculture and the Environment," *BioScience* 46(9) (1996), 665–673.

Palukaitis, P., "Virus-Mediated Genetic Transfer in Plants," in M. Levin and H. Strauss (eds.), *Risk Assessment in Genetic Engineering* (McGraw-Hill, New York, NY, 1991), pp. 140–162.

Parga V. M. and F. X. Flores, "Variedades Mexicanas de Papa en la Produccion de Alimentos Preservando el Ambiente," in *CONPAPA. Memorias del VI Congreso*

Nacional de Productores de Papa (Confederacion Nacional de productores de Papa, Saltillo, Mexico, 1995), pp. 65–69.

Person, C., “Gene-for-Gene Relationships in Host-Parasite Systems,” *Canadian Journal of Botany* 37 (1959), 1101–1130.

Pimentel, D., “Habitat Factors in New Pest Invasions,” in K. C. Kim and B. A. McPheron (eds.), *Evolution of Insects – Patterns of Variation* (J. Wiley & Sons, New York, 1993).

Pimentel, D., *Techniques for Reducing Pesticide Use. Economic and Environmental Benefits* (J. Wiley & Sons, New York, 1997).

Pimentel, D. and H. Lehman (eds.), *The Pesticide Question: Environment, Economics, and Ethics* (Chapman & Hall, New York, 1993).

Pimentel, D. and M. S. Ali, “An Economic and Environmental Assessment of Herbicide-Resistant and Insect/Pest Resistant Crops,” *Indian Journal of Applied Economics* 7(2) (1998), 241–252.

Pimentel, D. and A. Greiner, “Environmental and Socio-Economic Costs of Pesticide Use,” in D. Pimentel (ed.), *Techniques for Reducing Pesticide Use: Environmental and Economic Benefits* (J. Wiley & Sons, Chichester, UK, 1997), pp. 51–78.

Pimentel, D. and K. Hart, “Ethical, Environmental, and Public Health Implications of Pesticide Use,” Chapter in *New Perspectives in Bioethics* (Johns Hopkins University Press, 1999), in press.

Pimentel, D., A. Greiner, and T. Bashore, “Economic and Environmental Costs of Pesticide Use,” in J. Rose (ed.), *Environmental Toxicology: Current Developments* (Gordon and Breach Science Publishers, Amsterdam, The Netherlands, 1998), pp. 121–150.

Pimentel, D., H. Acquay, M. Biltonen, P. Rice, M. Silva, J. Nelson, V. Lipner, S. Giordano, A. Horowitz, and M. D’Amore, “Assessment of Environmental and Economic Impacts of Pesticide Use,” in D. Pimentel and H. Lehman (eds.), *The Pesticide Question: Environment, Economics, and Ethics* (Chapman & Hall, New York, 1993), pp. 47–83.

Quaim, M., “Transgenic Virus Resistant Potatoes in Mexico: Potential Socioeconomic Implications of North-South Biotechnology Transfer” *ISAAA Briefs* (Cornell University, 7/1998).

Reanova, V., V. Tuma, and K. Ondokova, “Effect of the Herbicide Roundup on Earthworms of the Family *Lumbricidae* in the Mountainous Meadow Ecosystems,” *Zootechnicka Rada, Ceske Budejovice* 13(2) (1996), 63–70.

Rice, M. E. and C. D. Pilcher, “Potential Benefits and Limitations of Transgenic Bt Corn for management of the European Corn Borer (*Lepidoptera: Crambidae*),” *American Entomologist* (Summer 1998), 75–78.

Rissler, J. and M. Mellon, *Perils Amidst the Promise: Ecological Risks of Transgenic Crops in a Global Market* (Union for Concerned Scientists, Cambridg, MA, 1993).

Rogers, H. J. and H. C. Parkes, “Transgenic Plants and the Environment,” *J. Exp. Bot.* 46 (1995), 467–488.

Roush, R. T. and J. A. McKenzie, “Ecological Genetics of Insecticide and Acaride Resistance,” *Annu. Rev. Entomol.* 32 (1987), 361–380.

Samsoe-Peterson, L., “Effects of 67 Herbicides and Plant Growth Regulators on the Rove Beetle *Aleochara bilineata* (*Col. Staphylinidae*) in the Laboratory,” *Entomophaga* 40 (1995), 95–104.

Santoni, S. and A. Berville, “Characterization of the Nuclear Ribosomal DNA Units and Phylogeny of Beta L. Wild Forms and Cultivated Beets,” *Theor. Appl. Genet.* 83 (1992), 533–542.

Smith, B. D., *The Emergence of Agriculture* (Scientific American Library, Washington, DC, 1995).

Smith, C. M., *Plant Resistance to Insects. A Fundamental Approach* (J. Wiley & Sons, New York, 1989).

Smith, J. R. and S. A. Leong, "Mapping of a Magnaporthe grisea Locus Affecting Rice (*Orysa sativa*) Cultivar Specificity," *Theoretical and Applied Genetics* 88(8) (1994), 901–908.

Springett, J. A. and R. A. J. Gray, "Effect of Repeated Low Doses of Biocides on the Earthworm *Apporectodea caliginosa* in Laboratory Culture," *Soil Biology and Biochemistry* 24(12) (1992), 1739–1744.

Steffey, K. L., "Crops, Genetic Technology, and Insect Management: Let's Talk," *American Entomologist* 41(4) (1995), 205–206.

Stone, W. B. and P. B. Gradoni, "Wildlife Mortality Related to the Use of the Pesticide Diazonin," *Northeastern Environmental Science* 4 (1985), 30–38.

Strizhov, N., M. Keller, J. Mathur, Z. Konz-Lalman, D. Bosch, E. Prudovsky, J. Schell, B. Sneh, C. Koncz, and A. Zilberstein, *Proceedings of the National Academy of Sciences* 93(26) (1996), 15012–15017.

Swan, S. H., E. P. Elkin, and L. Fenster, "Have Sperm Densities Declined? A Re-Analysis of Global Trend Data," *Environmental Health Perspectives* 105(11) (1997), 1228–1232.

Tabashnik, B. E., "Resistance Risk Management: Realized Heritability of Resistance to Bacillus thuringiensis in Diamond Back Moth (*Lepidoptera: Pluetellidae*), Tobacco Budworm (*Lepidoptera: Noctuidae*), and Colorado Potato Beetle (*Coleoptera: Chrysomelidae*)," *Journal of Economic Entomology* 85 (1992), 1551–1559.

Tepfer, M., "Viral Genes and Transgenic Plants," *Bio/Technology* 11 (1993), 1125–1129.

Tepfer, M., F. Vilaine, M. Carneiro, V. Pautot, C. Charbonnier, M. Rossignol, G. Vansuyt, E. Prinsen, H.Van-Onckelen, V. Legue, G. Perbal, C. Besnard, M. Noin, A. Guivarc'h, and D. Chriqui, "Physiological and Morphological Consequences of Expression of the rolA Gene in Transgenic Tobacco Plants," *Acta Botanica Gallica* 140(6), 685–691.

Tinney, R. T., *The Oil Drilling Prohibitions at the Channel Islands and Pt. Reyes-Fallallon Island National Marine Sanctuaries: Some Costs and Benefits* (Report to Center for Environmental Educations, Washington, DC, 1982).

UNEP, *Global Environmental Outlook* (United Nation Environmental Programme, Nairobi, Kenya, 1997).

USFWS, *1985 Survey of Fishing, Hunting, and Wildlife Associated Recreation. U.S. Fish and Wildlife Service* (U.S. Department of the Interior, Washington, DC, 1988).

Verderio, A., M. Bressan, M. Bertolini, S. Pino, G. Mazzinelli, and G. Sartori, "Risultati delle varieti transgeniche di mais resistenti a piralide o tolleranti a glufosinate-ammonio," *L'Informatore Agrario* 12(98) (1998), 61–70.

Waite, D. T., R. Grover, N. D. Westcott, D. G. Irvine, L. A. Kerr, and H. Sommerstad, "Atmospheric Deposition of Pesticides in a Small Southern Saskatchewan Watershed," *Environmental Toxicology and Chemistry* 14(7) (1995), 1171–1175.

Walgenbach, F. E., *Economic damage Assessment of Flora and Fauna Resulting from Unlawful Environmental Degradation* (Manuscript, California Department of Fish and Game, Sacramento, CA, 1979).

Watanabe, T. and T. Iwase, "Developmental and Dysmorphongenic Effects of Glufosinate Ammonium on Mouse Embryos in Culture," *Tetratogenesis, Carcinogenesis and Mutagenesis* 16(6) (1996), 287–299.

Wellings, C. R. and R. A. McIntosh, "*Puccina straiiformis F sp tririci* in Australia: Pathogenic Changes During First 10 Years," *Plant Pathology* (London) 39(2) (1990), 316–325.

White, D. H., C. A. Mitchell, L. D. Wynn, E. L. Flickinger, and E. J. Kolbe, "Organophosphate Insecticide Poisoning of Canada Geese in the Texas Panhandle," *Journal of Field Ornithology* 53 (1982), 22–27.

Wilkinson, C. F., "Introduction and Overview," in S.R. Baker and C.F. Wilkinson (eds.), *The Effects of Pesticides on Human Health, Proceedings of a Workshop May 9–11, 1988, Keystone, Colorado* (Princeton Scientific Publishing, Princeton, 1990), pp. 5–33.

WHO (World Health Organization), *Glyphosate* (WHO, Geneva, Switzerland, 1994).

Wrubel, R. P. and J. Gressel, "Are Herbicide Mixtures Useful for Delaying the Rapid Evolution of Resistance? A Case Study," *Weed Technology* 8 (1994), 635–648.

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