The Ecological Impacts of Transgenic Crops on Agroecosystem Health

Miguel A. Altieri
Department of Environmental Science, Policy, and Management, University of California, Berkeley, California

ABSTRACT

Transgenic crops are being deployed at increasing rates in agricultural landscapes worldwide. This leads to increasing genetic uniformity of agroecosystems and enhances farmers dependence on biotechnological innovations subject to proprietary regimes controlled by multinational corporations. As developed transgenic crops respond to market niches and opportunities, there has been little consideration of the ecological implications of their deployment. Existing ecological theory and emerging research data suggest that the massive planting of transgenic monocultures can create critical environmental impacts ranging from gene flow between transgenic crops and wild relatives, the creation of super-weeds and the rapid development of insect resistance, to impacts on soil fauna and nontarget organisms. The consequences of such effects on agroecosystem health are analyzed are herein.

INTRODUCTION

Genetic engineering is an application of biotechnology involving the manipulation of DNA and the transfer of gene components between species in order to achieve stable intergenerational expression of new traits. In fact, plant biotechnology is already changing farming practices and is likely to transform food production and impact the environment in dramatic ways (OTA 1992). During the 12-year period between 1986 and 1997, approximately 25,000 crop field trials were conducted globally on more than 60 crops with 10 traits in 45 countries (James 1997). The global arable land area devoted to transgenic crops increased 4.5-fold from 2.8 million hectares in 1996 to 12.8 million hectares in 1997, and no less than 30 million hectares in 1998. The United States accounted for 64% of the global acreage, followed by China and Argentina.

Although there are many applications of genetic engineering in agriculture, the current focus of biotechnology is to generate transgenic crops such as herbicide resistant crops (HRCs) and pest and disease resistant crops. HRCs and insect resistant (Bt) crops accounted for 54 and 31%, respectively, of the total global area in 1997. Increasingly, large acreages of transgenic soybean (18 million hectares), maize (10 million hectares), potato, tomato, tobacco, and cotton are being commercially deployed in agricultural landscapes worldwide (James 1997). Transnational corporations (TNCs), such as Monsanto, DuPont, and Norvartis, that are the main proponents of biotechnology, argue that carefully planned introduction of these crops should reduce or even eliminate the enormous crop losses due to weeds, insect pests, and pathogens. They argue that the use of such crops will have added beneficial effects on the environment by significantly reducing the use of agrochemicals. What is ironic is the fact that the biorevolution is being brought forward by the same interests that promoted the first wave of agrochemically based agriculture, but this time, by equipping each crop with new "insecticidal genes," they are promising the world safer pesticides, reduction on chemically intensive farming, and a more sustainable agriculture.

Address correspondence to: Miguel A. Altieri, University of California, Berkeley, ESPM-Division of Insect Biology, 201 Wellman-3112, Berkeley, CA 94720–3112; E-mail agroeco3@nature.berkeley.edu.

As long as transgenic crops follow closely the pesticide paradigm, such biotechnological products will do nothing but reinforce the pesticide treadmill in agroecosystems, thus legitimizing the concerns that many scientists have expressed regarding the possible environmental risks of genetically engineered organisms. Given the power of biotechnology to produce combinations of genes not found in nature, the most serious ecological risks posed by the commercial-scale use of transgenic crops are (Krimsky & Wrubel 1996; Rissler & Mellon 1996):

- The spread of transgenic crops threatens crop genetic diversity by simplifying cropping systems and promoting genetic erosion;
- The potential transfer of genes from HRCs to wild or semi-domesticated relatives, thus creating super weeds;
- HRC volunteers become weeds in subsequent crops;
- The use of HRCs undermine the possibilities of crop diversification thus reducing agrobiodiversity in time and space;
- Vector-mediated horizontal gene transfer and recombination to create new pathogenic bacteria;
- Vector recombination to generate new virulent strains of virus, especially in transgenic plants engineered for viral resistance with viral genes;
- Insect pests will quickly develop resistance to crops with Bt toxin;
- Massive use of Bt toxin in crops can unleash potential negative interactions affecting ecological processes and nontarget organisms including beneficial insects and soil biota.

The above impacts of agricultural biotechnology are herein evaluated in the context of agroecological goals aimed at making agriculture more socially just, economically viable, and ecologically sound (Altieri 1996). Such evaluation is timely given the explosion of transgenic crop cultivation worldwide, despite the fact that in most countries (especially in the developing world) stringent procedures are not in place to anticipate risk or to deal with environmental problems that may develop when engineered plants are released into the environment (Hruska & Lara Pavón 1997). This issue has received some discussion in government, international, and scientific circles, but often from a narrow perspective that has downplayed the seriousness of the risks (Kendall *et al.* 1997; Royal Society of London 1998). In fact, methods for risk assessment of transgenic crops are just being proposed (Kjellsson & Simonsen 1994), and there is justifiable concern that current field biosafety tests tell little about potential environmental risks associated with commercial-scale production of transgenic crops. A main concern is that international pressures to gain markets and profits is resulting in companies releasing transgenic crops too fast, without proper consideration for the long-term impacts on people or the ecosystem (Mander & Goldsmith 1996).

All of this has, in terms of the history of pesticide use, an aspect of déjà vu. The release of transgenic crops without consideration of long-term effects is likely to add a significant new set of threats to achieving agroecosystem health. Heretofore, this class of threats has not entered much into the discussion of agroecosystem health (Gallopin 1995; Smit *et al.* 1998), in part because transgenic crops are just now being produced and released in significant quantities, and the potential dangers are just now coming to light. An ecosystem health perspective ought to be highly relevant to the analysis—particularly the aspects of ecosystem health that bear on risks to human health with ecosystem breakdown (Epstein & Rapport 1996; Rapport *et al.* 1998a,b). The theme in this article is the identification of yet another potential major disrupter of ecosystem function and the great uncertainties that such disruption might portend, interacting with many other threats to the health of ecosystems, on the future state of the system (Levins 1995). In my view this topic merits major consideration as part of the research agenda for ecosystem health (Rapport *et al.* 1999).

ACTORS AND RESEARCH DIRECTIONS

Most innovations in agricultural biotechnology are profit driven rather than need driven, therefore the thrust of the genetic engineering industry is not really to solve agricultural problems but to create profitability. This statement is supported by the fact that at least 27 corporations have initiated herbicide-tolerant plant research, including the world's eight largest pesticide companies—Bayer, Ciba-Geigy, ICI, Rhone-Poulenc, Dow/Elanco, Monsanto, Hoescht, and DuPont—and virtually all seed companies, many of which have been acquired by chemical companies (Gresshoft 1996). Monsanto has acquired Dekalb, Asgrow, and Delta and Pineland, while AgrEvo acquired Sun Seeds and Dupont made an alliance with Pioneer. The buying of independent seed companies has concentrated the control of multinational companies over key genetic sources crucial for the improvement of agriculture (Hobbelink 1991).

In industrialized countries from 1986 to 1992, 57% of all field trials to test transgenic crops involved herbicide tolerance and 46% of applicants to the USDA for field testing were chemical companies. Crops currently targeted for genetically engineered tolerance to one or more herbicides include: alfalfa, canola, cotton, corn, oats, petunia, potato, rice, sorghum, soybean, sugarbeet, sugar cane, sunflower, tobacco, tomato, wheat, and cole crops. It is clear that by creating crops resistant to its herbicides a company can expand markets for its patented chemicals. Duke (1996), gave a value of $75 million for HRCs in 1995, the first year they were marketed, and indicated by the year 2000 the market will be approximately $805 million, representing a 61% growth. It is also estimated that by the year 2000, the market value of insecticide resistant crops will be about $500 million.

Although some testing is being conducted by universities and advanced research organizations, the research agenda of such institutions is being increasingly influenced by the private sector in ways not seen in the past. Forty-six percent of biotechnology firms support biotechnology research at universities, while 33 of the 50 states have university-industry centers for the transfer of biotechnology. The challenge for such organizations will not only be to ensure that ecologically sound aspects of biotechnology are researched and developed (nitrogen-fixing, drought tolerance, etc.), but to carefully monitor and control the provision of applied nonproprietary knowledge to the private sector so as to protect that such knowledge will continue in the public domain for the benefit of all society. But the current nature of university-industry partnerships, exemplified by the recent agreement between the University of California, Berkeley and Novartis, casts no doubt on how TNCs can control public research to their advantage.

BIOTECHNOLOGY AND AGROBIODIVERSITY

Although biotechnology has the capacity to create a greater variety of commercial plants, the trend set forth by TNCs is to create broad international markets for a single product, thus creating the conditions for genetic uniformity in rural landscapes. In addition, patent protection and intellectual property rights as espoused by the World Trade Organization (WTO), inhibiting farmers from re-using, sharing, and storing seeds raises the prospect that few varieties will dominate the seed market. Companies such as Monsanto make sure that farmers depend on their seeds by asking them to sign an agreement promising not to plant seeds their crops produce. Moreover, Monsanto hopes to enforce biologically what it cannot enforce contractually by designing crops whose seeds they carry will lose the ability to reproduce. Such seed-sterilizing technology has been dubbed “terminator technology” and poses major threats to one of the most viable methods of maintaining genetic diversity: the ability of farmers to store, re-plant, and share seeds. Although a certain degree of crop uniformity may have certain economic advantages, it has two ecological drawbacks. First, history has shown that a huge area planted to a single cultivar is vulnerable to new, matching strains of a pathogen or pest. And, second, the widespread use of a single cultivar leads to a loss of genetic diversity (Robinson 1996). Evidence from the Green Revolution clearly shows that the spread of modern varieties has been an important cause of genetic erosion, as massive government campaigns encouraged farmers to adopt modern varieties and to abandon many local varieties (Tripp 1996). The uniformity caused by increasing areas sown to a smaller number of varieties is a source of increased risk for farmers, as the varieties may be more vulnerable to disease and pest attack and most of them perform poorly in marginal environments (Robinson 1996).

All the above effects are not ubiquitous to modern varieties but it is expected that, given their monogenic nature and fast acreage expansion, transgenic crops will only exacerbate such effects.

ENVIRONMENTAL PROBLEMS OF HRCs

According to proponents of HRCs, this technology represents an innovation that enables farmers to simplify their weed management requirements by reducing herbicide use to postemergence situations using a single, broad-spectrum herbicide that breaks down relatively rapidly in the soil. As subsidies drop, it may no longer be economical to control weeds with expensive herbicides, thus, developing HRCs for lower-cost herbicides may be the solution. Herbicide candidates with such characteristics include glyphosate, bromoxynil, sulfonylurea, imidazolinones, and glufosinate ammonium, among others.

But, in actuality, the use of HRCs is likely to increase the use of specific herbicides, and given herbicide volumes and acreage coverage (in 1997 50,000 farmers grew 3.6 million hectares of herbicide resistant soybeans, equivalent to 13% of the 71 million national soybean acreage in the United States), production costs are likely to increase. Although industry claims that HRCs have enhanced yield dependability, soil, and water conservation, and are compatible with minimum tillage systems, ecologists predict a number of serious environmental problems associated with such crops.

HERBICIDE RESISTANCE

It is well documented that when a single herbicide is used repeatedly on a crop the chances of herbicide resistance developing in weed populations greatly increases (Holt *et al.* 1993). About 216 cases of pesticide resistance have now been reported in one or more herbicide chemical family (Holt & Le Baron 1990). Triazine herbicides have the most resistant weed species (about 60), but the sulfonylureas and the imidazolinones are also particularly prone to the rapid evolution of resistant weeds, and currently 14 weed species have become resistant to sulfonylurea herbicides. Cocklebur, an aggressive weed of soybean and corn in the southeastern United States, has exhibited resistance to imidazolinone herbicides. Many weed grasses now exhibit multiple herbicide resistances (Goldberg 1992).

The problem is that, given industry pressures to increase herbicide sales, acreage treated with these broad-spectrum herbicides will expand, exacerbating the resistance problem. For example, it has been projected that the acreage treated with glyphosate will increase to nearly 150 million acres. Although glyphosate is considered less prone to weed resistance, the increased use of the herbicide will result in weed resistance, even if more slowly, as it has been already documented with Australian populations of annual ryegrass, quackgrass, birdsfoot trefoil, and *Cirsium arvense* (Gill 1995).

ECOLOGICAL IMPACTS OF HERBICIDES

Companies affirm that bromoxynil and glyphosate, when properly applied, degrade rapidly in the soil, do not accumulate in groundwater, have no effects on nontarget organisms, and leave no residues in food. There is, however, evidence that bromoxynil causes birth defects in laboratory animals, is toxic to fish, and may cause cancer in humans (Goldberg 1992). Because bromoxynil is absorbed dermally, and because it causes birth defects in rodents, it is likely to pose hazards to farmers and farm workers. Similarly glyphosate has been reported to be toxic to some nontarget species in the soil—both to beneficial predators such as spiders, mites, carabid, and coccinellid beetles, and to detritivores such as earthworms, as well as to aquatic organisms, including fish (Pimentel *et al.* 1989). As this herbicide is known to accumulate in fruits and tubers as it suffers little metabolic degradation in plants, questions about food safety also arise.

TRANSGENIC CROPS AS WEEDS

Some scientists have suggested that some transgenes may confer or enhance weediness in some crops, thereby enhancing their capacity to persist in agricultural fields. Most genetically engineered plants would not be expected to become weeds; those that do, however, present serious problems (Radosevich *et al.* 1996). This is the case of transgenic seeds that at harvest shatter to the ground and germinate the following year in rotational crops. If these "volunteer weeds" are resistant to herbicides being used in the new crop, competition may become critically yield limiting.

CREATION OF "SUPER WEEDS"

Although there is some concern that transgenic crops themselves might become weeds, a major ecological risk is that large-scale releases of transgenic crops may promote transfer of transgenes from crops to other plants, which may then become weeds (Darmency 1994). Transgenes that confer significant biological advantages may transform wild/weedy plants into new or worse weeds (Rissler & Mellon 1996). The biological process of concern here is introgression, that is, hybridization among distinct plant species. Evidence indicates that such genetic exchanges among wild, weed, and crop plants already occur. The incidence of shattercane (*Sorghum bicolor*), a weedy relative of sorghum, and the gene flows between maize and teosinte, demonstrate the potential for crop relatives to become serious weeds. This is worrisome given that a number of U.S. crops are grown in close proximity to sexually compatible wild relatives (Lutman 1999). Extreme care should be taken in plant systems exhibiting easy cross-pollination such as oats, barley, sunflowers, and wild relatives, and between rapeseed and related crucifers. In Europe there is major concern about the possibility of pollen transfer to herbicide tolerant genes from *Brassica* oilseeds to *Brassica nigra* and *Sinapis arvensis* (Casper & Landsmann 1992) There are also crops that are grown near wild/weedy plants that are not close relatives but may have some degree of cross compatibility, such as the crosses of *Raphanus raphanistrum* R. × *Sativus* (radish) and Johnson grass × Sorghum corn (Radosevich *et al.* 1996). Cascading repercussions of these transfers may ultimately mean changes in the make-up of plant communities and may pose major threats to centers of diversity. Transfer of genes from transgenic crops to organically grown crops poses specific problems to organic farmers as organic certification depends on the growers being able to guarantee that their crops have no inserted genes. Crops able to outbreed, such as maize or oilseed rape, will be affected to the greatest extent, but all organic farmers are at risk of contamination as there are no regulations that enforce minimum isolating distances between transgenic and organic fields.

REDUCTION OF AGROECOSYSTEM COMPLEXITY

Total weed removal via the use of broad-spectrum herbicides may lead to undesirable ecological impacts given that an acceptable level of weed diversity in and around crop fields has been documented to play important ecological roles such as enhancement of biological insect pest control, better soil cover reducing erosion, etc. (Altieri 1994). HRCs will probably enhance continuous cropping by inhibiting the use of rotations and polycultures susceptible to the herbicides used with HRCs. Such impoverished, low plant diversity agroecosystems provide optimal conditions for unhampered growth of weeds, insects, and diseases because many ecological niches are not filled by other organisms. Moreover, HRCs, through increased herbicide effectiveness, could further reduce plant diversity, favoring shifts in weed community composition and abundance, favoring competitive species that adapt to these broad-spectrum, post emergence treatments (Radosevich *et al.* 1996).

ENVIRONMENTAL RISKS OF INSECT RESISTANT CROPS

RESISTANCE

According to the industry, the promise of transgenic crops inserted with Bt genes is the replacement of synthetic insecticides now used to control insect pests. The gene coding for Bt toxin production was introduced into cotton and the first commercial planting of transgenic cotton occurred in 1996. Productivity was higher than for nontransgenic cotton, but was not as high as expected. Problems arose in the States because of a particularly heavy infestation of bollworm in 800,000 hectares, causing heavy feeding damage. The infestation was controlled using conventional insecticides (Peferoen 1997). Because most crops have a diversity of insect pests, insecticides will still have to be applied to control non-Lepidoptera pests, which are not susceptible to the endotoxin expressed by the crop (Gould 1994). In a recent report (USDA 1999), an analysis of pesticide use in the 1997 growing season in 12 region/crop combinations showed no statistically significant differences in pesticide use on Bt crops versus non-Bt crops in seven sites. In the Mississippi Delta, significantly more pesticides were used on Bt versus non-Bt cotton.

However, several Lepidoptera species have been reported to develop resistance to Bt toxin in both field and laboratory tests, suggesting that major resistance problems are likely to develop in Bt crops which through the continuous expression of the toxin create a strong selection pressure (Tabashnik 1994). Industry, however, claims that transgenic plants expressing high levels of endotoxin represent a different type of selection pressure that is a chronic high-dose exposure. No reports of resistance to chronic high-dose exposure of Bt endotoxins are yet known. Moreover, given that a diversity of different Bt-toxin genes have been isolated, biotechnologists argue that if resistance develops, alternative forms of Bt toxin can be used (Kennedy & Whalon 1995). Because insects are likely to develop multiple resistance or cross-resistance, this strategy is also doomed to fail (Alstad & Andow 1995). Scientists have already detected development of "behavioral resistance" by some insects that take advantage of the fact that expression of toxin potency is uneven within crop foliage, thus attacking tissue patches with low toxin concentrations. Moreover, as genetically inserted toxins often decrease in leaf and stem titer as crops reach maturation, the low dose can only kill or debilitate completely susceptible larvae (homozygotes) and consequently adaptation to the Bt toxin can occur much faster if the concentration always remained high. Observation of transgenic corn plants in late October indicated that most European corn borers that survived had entered diapause in preparation for emergence in the following spring as adults (Onstad & Gould 1998).

Others, borrowing from past experience with pesticides, have proposed resistance management plans with transgenic crops, such as the use of seed mixtures and refuges (Tabashnik 1994). Patchworks of transgenic and nontransgenic crops can delay the evolution of resistance by providing susceptible insects for mating with resistant insects. The crops in the refuge are likely to sustain heavy damage; a refuge kept completely free of pesticides must be 20–30% the size of the engineered plot. The refuge should be about 40% the size of the biotechnology plot if pesticides are to be used, since insecticide spraying can increase the odds of Bt resistance developing. According to members of the Campaign for Food Safety, Monsanto's new plan calls for only 20% refuges even when insecticides are to be used. Moreover, the plan offers no details whether the refuges must be planted alongside the transgenic crops, or at some distance away, where studies suggest they would be less effective (Mallet & Porter 1992). Recent laboratory results with a worldwide pest, the pink bollworm, contradict an important assumption of the refuge strategy. Liu *et al.* (1999) found that a resistant pink bollworm larva strain on Bt cotton took longer to develop than susceptible larvae on non-Bt cotton. This development asynchrony favors random mating that could reduce the expected benefits of the refuge strategy.

In addition to the difficult goal of requiring regional coordination between farmers, it is unrealistic to expect most small- and medium-sized farmers to devote up to 30–40% of their crop area to refuges, especially if crops in these areas are to sustain heavy pest damage. It is likely that development of resistance will be influenced both by the insect and crop in question. For example, it may be argued that for the European corn borer, that has a low number of generations per year and feeds on numerous other host plants besides corn, resistance is a small issue. However, given the rapid expansion of transgenic crop monocultures worldwide (from 2.8 million hectares in 1996 to 34 million in 1998) that occur at the expense of natural vegetation and other crops, the availability of alternate host plants can decrease considerably (Kendall *et al.* 1997).

EFFECTS ON BENEFICIAL INSECTS

By keeping pest populations at extremely low levels, Bt crops could potentially starve the natural enemies of pests, as these beneficial predator insects need a small amount of prey to survive in the agroecosystem. Among the natural enemies that live exclusively on insects that the transgenic crop is designed to kill (Lepidoptera), egg and larval parasitoids would be most affected because they are totally dependent on live hosts for development and survival, whereas some predators could theoretically thrive on dead or dying prey.

Natural enemies could also be affected directly through intertrophic level effects of the toxin. The potential of Bt toxins moving through arthropod food chains poses serious implications for natural biocontrol in agroecosystems. In Scotland, Birch (1997), working with transgenic lectin (GNA) expressing plants (not commercially available yet), found that GNA exhibited sublethal effects on aphids in turn affecting reproduction and longevity of beneficial coccinellid predators. Similarly, studies in Switzerland show that mean total mortality of Lacewing larvae (Chrysopidae) raised on Bt fed prey was 62% compared with 37% when raised on Bt-free prey. Bt prey fed Chrysopidae also exhibited prolonged development time throughout their immature life stage (Hilbeck *et al.* 1998). In studies involving the diamondback moth and its parasitic wasp (*Cotesia plutellae*), parasitic larvae forced to develop in Bt-treated susceptible moth larvae inevitably died with their hosts (Schuler *et al.* 1999). These results could be questioned on the basis that they came from small-scale laboratory assays in which insects were exposed to high levels of transgenically expressed toxin in no-choice tests. But such no-choice situations will increasingly become the norm in field conditions as Bt crops massively inundate the landscape.

EFFECTS ON SOIL BIOTA

Bt toxins can be incorporated into the soil through leaf materials when farmers incorporate crop residues after harvest. Toxins may persist for 2–3 months, resisting degradation by binding to clay and humic acid soil particles while maintaining toxin activity (Palm *et al.* 1996). Such active Bt toxins that end up and accumulate in the soil and water from transgenic leaf litter may have negative impacts on soil and aquatic invertebrates and nutrient cycling processes (Donnegan *et al.* 1995).

Perturbations have been recorded by several authors with the introduction in the soil of genetically modified microorganisms (such as *Pseudomonas fluorescens*), including displacement of indigenous populations, suppression of fungal populations, reduced protozoa populations, altered soil enzymatic activity, and increased carbon turnover (Naseby & Lynch 1998). These authors call for more research on the consequences of the release of novel organisms in the rhizosphere before they can be safely utilized.

DOWNSTREAM EFFECTS

A major environmental consequence resulting from the massive use of Bt toxin in cotton or other crops occupying a larger area of the agricultural landscape is that neighboring farmers who grow crops other than cotton, but that share similar pest complexes, may end up with resistant insect populations colonizing their fields. As Lepidopteran pests that develop resistance to Bt cotton move to adjacent fields where farmers use Bt as a microbial insecticide, this may render farmers defenseless against such pests as the biopesticide becomes ineffective, thus losing an important biological control tool (Gould 1994). Among those most affected would be organic farmers who rely on Bt-based microbial insecticides for their pest management programs. Recent findings by Losey *et al.* (1999), showing that corn pollen containing Bt toxin can drift several meters downwind and deposit itself on milkweed foliage with potentially deleterious effects on monarch butterfly populations, opens a whole new dimension on the unexpected impacts of transgenic crops on nontarget organisms.

IMPACTS OF DISEASE RESISTANT CROPS

Scientists have attempted to engineer plants for resistance to pathogenic infection by incorporating genes for viral products into the plant genome. The most common method is to use viral RNA sequences which when inserted into plants and expressed, interfere with the infecting virus to give what is called "pathogen-derived protection." Although the use of viral genes for resistance in crops to viruses has potential benefits, there are some risks. First, in plants containing coat protein genes, there is a possibility that such genes will be taken up by unrelated viruses infecting the plant. In such situations, the foreign gene changes the coat structure of the viruses and may confer properties such as changed method of transmission between plants. The second potential risk is that recombination between RNA virus and a viral RNA inside the transgenic crop could produce a new pathogen leading to more severe disease problems. Some researchers have shown that recombination occurs in transgenic plants and that under certain conditions it produces a new viral strain with an altered host range (Steinbrecher 1996).

The possibility that transgenic virus-resistant plants may broaden the host range of some viruses or allow the production of new virus strains through recombination and transcapsidation demands careful further experimental investigation (Paoletti & Pimentel 1996).

THE PERFORMANCE OF FIELD-RELEASED TRANSGENIC CROPS

Up to 1995 more than 2000 small-scale field trials of genetically engineered plant species have been carried out in the United States. Until early 1997, 13 genetically modified crops had been deregulated by the USDA that were already on the market or in the fields for the first time. Over 20% of the U.S. soybean acreage was planted with Roundup-tolerant soybean and about 400,000 acres of Maximizer Bt corn were planted in 1996. Worldwide such acreage expanded considerably in 1998 (transgenic cotton, 6.3 million acres; transgenic corn, 20.8 million acres; soybean, 36.3 million acres) due to marketing and distribution agreements entered into by corporations and marketers (i.e., Ciba Seeds with Growmark and Mycogen Plant Sciences with Cargill).

Given the speed with which products move from laboratory testing to field production, the question arises whether transgenic crops meet the expectations of the biotechnology industry. According to evidence presented by the Union of Concerned Scientists (1996), there are already signals that the commercial-scale use of some transgenic crops pose serious ecological risks and do not deliver the promises of industry (Table 1). A recent study by the USDA Economic Research Service (USDA 1999) shows that in 1998 yields were not significantly different in engineered versus nonengineered crops in 12 of 18 crop/region combinations. In the six crop/region combinations where Bt crops or HRCs fared better, they exhibited increased yields between 5 and 30%. Glyphosphate-tolerant cotton showed no significant yield increase in either region where it was surveyed.

The appearance of "behavioral resistance" by bollworms in cotton, i.e., that the herbivore was capable of finding plant tissue areas with low Bt concentrations, raises questions not only about the adequacy of the resistance management plans being adopted, but also about the way biotechnologists underestimate the capacity of insects to overcome genetic resistance in unexpected manners (Biotechnology and Development Monitor 1996).

Similarly poor harvests of herbicide resistant cotton due to phytotoxic effects of Roundup in 4000–5000 acres in the Mississippi Delta (*New York Times* 1997) points at the erratic performance of HRCs when subjected to varying agroclimatic conditions. Monsanto claims that this is a very small and localized incident that is being used by environmentalists to overshadow the benefits that the technology brought on 800,000 acres. From an agroecological standpoint, however, this incident is quite significant and merits further evaluation, since assuming that a homogenizing technology will perform well through a range of heterogeneous conditions has no scien-

TABLE 1

Field performance of some recently released transgenic crops

Transgenic Crop Released	Performance	Reference
1. Bt transgenic cotton	Additional insecticide sprays needed due to Bt cotton failing to control bollworms in 20,000 acres in eastern Texas	Kaiser (1996); Peferoen (1997)
2. Cotton inserted with Roundup Ready© gene	Bolls deformed and falling off in 4000–5000 acres in Mississippi Delta	Lappe & Bailey (1997); Myerson (1997)
3. Bt corn	27% yield reduction and lower Cu foliar levels in Beltsville trial	Hormick (1997)
4. Herbicide resistant oilseed rape	Pollen escaped and fertilized botanically related plants in 2.5 km away in Scotland	Scottish Crop Research Institute (1996)
5. Virus resistant squash	Vertical resistance to two viruses and not to others transmitted by aphids	Rissler, J. (Personal communication)
6. Early FLAVR-SAVR tomato varieties	Did not exhibit acceptable yields and disease resistance performance	Biotech Reporter (1996)
7. Roundup Ready Canola	Pulled off the market due to contamination with a gene that did not have regulatory approval	J. Rissler (personal communication)
8. Bt potatoes	Aphids sequestered the Bt toxin affecting coccinellid predators in negative ways	Birch (1997)
9. Herbicide tolerant crops	Development of resistance by annual ryegrass to Roundup	Gill (1995)

tific basis. There is also much concern about the fact that the hundreds of small-scale tests carried out mostly by private companies do not capture the full dimension of the environmental fate of field-deployed transgenic crops. Tests are usually limited to prevent escape of pollen, seeds, or other propagules. Experimental tests are usually carried in small plots and are of short duration (one season) and thus undesirable effects on nontarget organisms are unlikely to be observed (Snow & Moran 1997).

CONCLUSIONS

We know from the history of agriculture that plant diseases, insect pests, and weeds become more severe with the development of monoculture, and that intensively managed and genetically manipulated crops soon lose genetic diversity (Altieri 1994; Robinson 1996). Given these facts, there is no reason to believe that resistance to transgenic crops will not evolve among insects, weeds, and pathogens as has happened with pesticides. No matter what resistance management strategies will be used, pests will adapt and overcome the agronomic constraints (Green *et al.* 1990). Studies of pesticide resistance demonstrate that unintended selection can result in pest problems that are greater than those that existed before deployment of novel insecticides. Diseases and pests have always been amplified by changes toward homogeneous agriculture (Robinson 1996).

The fact that interspecific hybridization and introgression are common to species such as sunflower, maize, sorghum, oilseed rape, rice, wheat, and potatoes provides a basis to expect gene flow between transgenic crops and wild relatives to create new herbicide-resistant weeds (Lutman 1999). There is consensus among scientists that transgenic crops will eventually allow transgenes to escape into free-living populations of wild relatives. The disagreement lies in how serious are the impacts (Casper & Landsmann 1992). Despite the fact that some scientists argue that genetic engineering is not different than conventional breeding, critics of biotechnology claim that DNA technology enables new (exotic) genes into transgenic plants. Such gene transfers are mediated by vectors derived from disease-causing viruses or plasmids that can break down species barriers so they can shuttle genes between a wide range of species, thus infecting many other organisms in the ecosystem (Steinbrecher 1996).

The ecological effects are not limited to pest resistance and creation of new weeds or virus strains. As argued herein, transgenic crops can produce environmental toxins that move through the food chain and also may end up in the soil and water, affecting invertebrates and possibly ecological processes such as nutrient cycling. Moreover, the large-scale landscape homogenization with transgenic crops will exacerbate the ecological problems already associated with monoculture agriculture. Unquestioned expansion of this technology into developing countries may not be wise or desirable. There is strength in the agricultural diversity of many of these countries and it should not be inhibited or reduced by extensive monoculture, especially when consequences of doing so results in serious social and environmental problems (Lappe *et al.* 1998).

Many environmental groups have argued for the creation of suitable regulation to mediate the testing and release of transgenic crops to offset environmental risks, and demand a much better assessment and understanding of ecological issues associated with genetic engineering. This is crucial, as many results emerging from the environmental performance of released transgenic crops suggest that in the development of "resistant crops," not only is there a need to test direct effects on the target insect or weed, but the indirect effects on the plant (i.e., growth, nutrient content, metabolic changes), soil, and nontarget organisms must also be evaluated. Unfortunately, funds for research on environmental risk assessment are very limited. For example, the USDA spends only 1% of the funds allocated to biotechnology research on risk assessment, about $1–2 million per year. Given the current level of deployment of genetically engineered plants, such resources are not enough to even discover the "tip of the iceberg."

Many scientists and sustainable agriculture advocates demand continued support for ecologically based agricultural research, as all the biological problems that biotechnology aims at can be solved using agroecological approaches. The dramatic effects of rotations and intercropping on crop health and productivity, as well as of the use of biological control agents on pest regulation, have been confirmed repeatedly by scientific research (Altieri 1994; NRC 1996). The problem is that research at public institutions increasingly reflects the interests of private funders at the expense of public good research such as biological control, organic production systems, and general agroecological techniques

(Busch *et al.* 1990). Civil society must request more research on alternatives to biotechnology by universities and other public organizations. There is also an urgent need to challenge the patent system and intellectual property rights intrinsic to the World Trade Organization (WTO), which not only provides multinational corporations with the right to seize and patent genetic resources, but that will also accelerate the rate at which market forces already encourage monocultural cropping with genetically uniform transgenic varieties. Based on history and ecological theory, it is not difficult to predict the negative impacts of such environmental simplification on the health of modern agriculture.

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