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The rapid emergence of genetic modification in world agriculture: contested risks and benefits

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Summary

There has been a rapid expansion in the commercial cultivation of genetically modified crops, rising from the first plantings in 1995 to 44.5 million hectares worldwide in 2000, most of which have grown in North America. Though there are sharp divisions in opinions on benefits and risk, genetic modification (GM) does not represent a single, homogenous technology. Each application brings different potential benefits and risks for different stakeholders. This paper reviews recent scientific progress and future applications using a new typology of three generations of genetically modified organisms (GMOs) ranged against five types of scientific application. Agricultural GMOs pose a range of potential environmental and health risks. An analysis of recent independent field and scientific evidence from industrialized countries summarizes the current state of knowledge on seven types of risk that apply to all agricultural systems: (1) horizontal gene flow; (2) new forms of resistance and pest problems; (3) recombination to produce new pathogens; (4) direct and indirect effects of novel toxins; (5) loss of biodiversity from changes to farm practices; (6) allergenic and immune system reactions; and (7) antibiotic resistance marker genes. There remain highly contrasting positions taken by different stakeholders over GMOs. A review of three debates explains claims and counter-claims for (1) genetic modification as technological fix or contributor to sustainability; (2) genetic modification as driver of corporate power or friend of farmer; and (3) genetic modification as feeder of the world or eliminator of alternatives.

Keywords: genetic modification, biodiversity, environmental risks, heath risks, sustainable agriculture, biosafety

Introduction

Biotechnology involves making molecular changes to living or almost-living things. It has a long history, dating back four thousand years to the development of fermentation, bread-making, brewing and cheese making by Egyptians and Sumerians, and later of grafting techniques by the Greeks. Modern biotechnology (also known as genetic modification or engineering) is, by contrast, the name given to the transfer of DNA (usually chromosomal) from one organism to another, so allowing the recipient to express traits or characteristics normally associated just with the donor (Conway 2000; Royal Society *et al*. 2000). As these transfers or mixes do not occur in nature, the scope for genetic modification is greater than in conventional animal or plant breeding, even though advanced breeding already involves types of genetic manipulation, including clonal propagation, embryo transfer, embryo rescue and mutant selection.

The expansion in the development and commercial cultivation of a few types of genetically modified (GM) crops has been extraordinarily rapid in recent years. Yet, many people are concerned about the potential direct and indirect environmental and health risks. As a large number of new GM technologies are under development, and most countries are yet to give approval for their cultivation, there is a pressing need to develop rigorous policies based on a sound understanding of the scientific evidence for their positive and negative effects. The objectives of this paper are thus:

(1) to review recent progress and future applications using a novel typology of three generations of genetically-modified organisms (GMOs) ranged against five types of scientific application;
(2) to analyse recent independent field and scientific evidence on the current state of knowledge for seven types of environmental and health risk: (i) horizontal gene flow; (ii) new forms of resistance and pest problems; (iii) recombination to produce new pathogens; (iv) direct and indirect effects of novel toxins; (v) loss of biodiversity from changes to farm practices; (vi) allergenic and immune system reactions; and (vii) antibiotic resistance marker genes; and
(3) to contrast the concerns and contested positions of different stakeholders in agricultural and food systems, relating these to both the structure and political economy of world agriculture and to the emergence of novel technologies.

Rapid growth in the early years

There are five major types of application of genetic modification for agriculture.

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(1) Gene inactivating techniques to reduce or switch off activity of specific undesired genes.
(2) Introduction of new genes or enhancement of existing gene action for amending flavour or colour, or modifying starch and oil content; and enhancing nutritional content of crop ('nutraceuticals') or pharmaceutical content of crop or animal.
(3) Introduction of genes for enhancing resistance to herbicides, pests and pathogens; enhancing resistance to environmental stresses; and modifying the external environment.
(4) Introduction of genes to enhance production of hybrids or to modify seed production by inducing apomixis (so fixing hybrid vigour).
(5) Adjusting switching mechanisms through promoters to turn on and off traits.

The greatest commercial growth has been in only one type of application, namely crops containing one of the two following traits (and increasingly both).

(1) herbicide tolerance (HT; also known as herbicide resistance, mainly to glyphosate and glufosinate ammonium), introduced in soya, oil seed rape (canola), cotton, maize and sugar beet, which allows the application of broad-spectrum herbicides to the standing crop, so killing all the weeds without causing the crop damage (approximately 28 million ha in 1999, and a further 2.9 million ha with crops containing the additional *Bacillus thuringiensis* [*Bt*] trait);
(2) insect resistance through *Bt* expression (there are many strains of *Bt* and at least 60 different crystal [Cry] proteins: Lepidoptera are affected by *Bt kurstaki*, mosquitoes and flies by *Bt israelensis* and beetles by *Bt tenebrionis*), mainly in maize and cotton, which means that the *Bt* insecticidal toxin is expressed by all cells of the plant, so killing susceptible herbivorous pests and so reducing the need to apply conventional insecticides (approximately 8.9 million ha grown in 1999, and a further 2.9 million ha additionally stacked with HT traits).

There has been a rapid expansion in the cultivation of these crops derived from genetic modification (GM) in recent years (Fig. 1). The first commercially cultivated GM crop was GM soya in 1995. By 1996, there were 1.7 million hectares of GM soya bean planted (not counting China), rising rapidly to 40 million ha in 1999, though then slowing to 44.5 million ha in 2000 (EPA 1999; James & Krattiger 1999; Chen 2000; Kydd *et al.* 2000; James 2001).

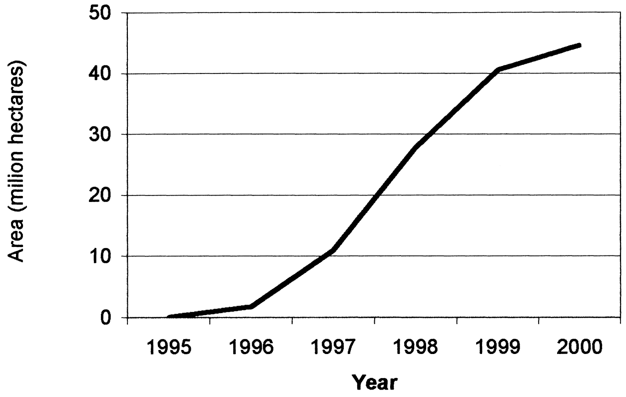

Figure 1 Commercially-cultivated GM crops in all countries (1995–2000). Sources: EPA 1999; Chen 2000; Kydd *et al.* 2000; James 2001.

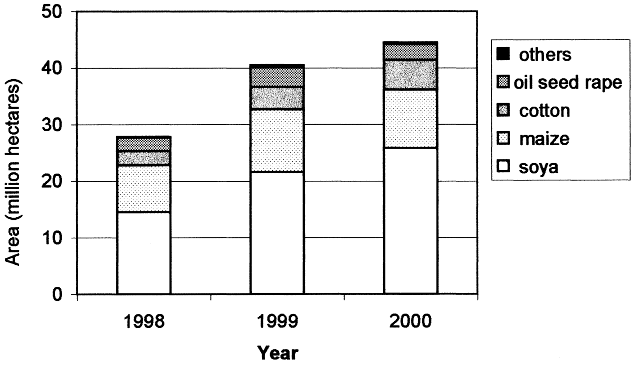

Figure 2 Amount of each GM crop commercially-cultivated (1998–2000). Sources: EPA 1999; Chen 2000; Kydd *et al.* 2000; James 2001.

In the year 2000, most GMOs were cultivated in the USA (68%), Argentina (23%), Canada (7%), with 25–100 000 ha each in Australia, Mexico, Spain, and South Africa; and there were about 1000 ha each in Bulgaria, France, Romania, Uruguay and Ukraine (Portugal grew a small amount in 1999, but then withdrew consent for 2000). In the UK, experimental field releases of GM plants have occurred on 300 ha. There are 400–500 000 ha of GM tobacco and cotton planted in China (Chen 2000; James 2001). Of the total 44.5 million ha planted worldwide in 2000, 58% was soya, 23% maize, 12% cotton and 6% oil seed rape (Fig. 2). Other GM crops include potato, squash and papaya.

Typology for different generations of GMOs

Only a few years after the development of the first GM crops for agriculture, there are sharp divisions in the opinions on benefits and risk. Some argue that GMOs are safe and essential for world progress; others state they are not needed, and hold too many risks. The first group believes that media manipulation and scaremongering are limiting useful technologies; the second that scientists, private companies and regulators are understating hazards for the sake of economic returns (cf. House of Lords Select Committee on the European Communities 1998; Royal Society 1998; British Medical Association 1999; Nuffield Council on Bioethics 1999; Royal Society *et al.* 2000).

Neither view is entirely correct, for one simple reason. GMOs are not a single, homogenous technology. Each application and product brings different benefits for different stakeholders, each poses different environmental and health risks. It is important, therefore, to distinguish both between the five major types of GM application (Table 1) and three different generations of GM technologies.

(1) The first generation technologies came into commercial use in the late 1990s, and have tended to bring few distinct consumer benefits. The realization of promised benefits to farmers and the environment has only been patchy, as these technologies have tended to benefit mainly the companies producing them; herbicide-tolerant soya, for example, locks farmers into buying the herbicide produced by the company marketing the GM seed. *Bt* maize and cotton permits reduced use of insecticides, so saving farmers money, but companies currently recover much of the margin through increased seed costs.
(2) The second generation technologies comprise those already developed and tested, but not commercially-released, either because of uncertainties over the stability of the technology itself, or over concerns for potential environmental risks. Some of these applications will clearly bring more public and consumer benefits, and include a range of medical applications.
(3) The third generation technologies are those that are still far from market, but generally require the better understanding of whole gene complexes that control such traits as drought- or salt-tolerance, and nitrogen fixation. These, again, are likely to bring more explicit consumer benefits than the first generation.

An example of a second-generation technology is the so-called 'Terminator' technology (as dubbed by campaigners), otherwise known as the Technology Protection System, or Genetic Use-Restriction Technology. This involves the insertion of gene-switching mechanisms to prevent any seed saved after harvest from germinating. This could have good or bad consequences. It would prevent the spread of genes from GMOs to wild relatives. However, it would also prevent farmers from reusing seed. As most farmers in developing countries save their seed, as do a surprisingly large number in industrialized countries (20–30% of US soya farmers reuse seed, and many wheat farmers only return to the market to buy seed once every 4–5 years), this technology effectively transfers power from farmers to companies (RAFI 1998). It has not surprisingly come in for substantial criticism.

Many of the third generation GMOs are, by contrast, more public-good oriented, though clearly none are without risk. If crops are developed with thermo-, drought-, salt- or metal-tolerance, these could make a substantial difference for farmers on problem soils or in difficult climates. Physiological modifications of rice and wheat could mean faster growth with existing nutrient, light and water resources, allowing farmers to benefit without being locked into new corporate dependencies. Modifications of crops with low value in rotations, such as legumes and oats, could make them more attractive to farmers because of high protein and energy content. Others could be more efficient in nitrogen use, so reducing nitrate leaching or nitrous oxide losses.

A considerable breakthrough in plant breeding would occur with the transfer of apomictic traits (the production of exact clones of the mother plant through asexual reproduction) into cereals. Research underway in Mexico at the International Centre for Maize and Wheat Research (CIMMYT) is, for example, seeking to transfer apomixis (involving several genes) from a grassy relative of maize, *Tripsacum dactyloides,* to maize itself. This would allow farmers to save the seed for subsequent seasons, so boosting the yields of poorer and remote farmers, provided a means could be found to get the new seeds to them when needed.

There are already concerns, however, that many of the methodologies and products in this process of GM apomixis transfer are being privately patented, and so will not become available to poorer farmers. In 1998, the Bellagio Apomixis Declaration (1998) was formulated, with scientific signatories sharing a concern that the 'current trend towards consolidation of plant biotechnology ownership in a few hands may severely restrict affordable apomixis technology, especially for resource poor farmers'.

The environmental and health risks of GM crops

Agricultural GMOs pose a range of potential environmental and health risks (Rissler & Melon 1996; Altieri 1998; Pretty 1998; House of Lords Select Committee on the European Communities 1998; Royal Society 1998; British Medical Association 1999; Nuffield Council on Bioethics 1999; ACRE 2000*a*, *b*). These include five types of potential environmental risk and two risks for human health. The degree to which each of these poses an actual risk is a combination of both a hazard and exposure, as not all hazards constitute a risk in practice. Each of these is analysed below in light of recent unaligned scientific knowledge, particularly drawing upon analyses from the field.

Potential environmental risks

Gene flow

The first potential environmental risk is gene flow, where transgenes could transfer from a GMO to wild relatives and/or bacteria in soil or human guts. Gene flow is a natural phenomenon (Ellstrand *et al.* 1999), with many species of plants crossing with related species, and so the question of novel risk rests on whether the transgenes could lead to the transfer of undesirable traits, and the emergence of permanently transformed populations. As these transfers have not occurred in nature, it is impossible to predict the effects with confidence (Raybould & Gray 1993; Chevré *et al.* 1997;

Table 1 GM applications and examples according to three generations of products (adapted from Pretty 1999, 2000*a*).

	First generation (in commercial use by late 1990s)	*Second generation (developed by late 1990s, but not yet commercially released)*	*Third generation (research underway, not yet close to market)*
Gene inactivating techniques to reduce or switch off activity of specific undesired genes	Long-life tomatoes	Fruit and vegetables with longer shelf-life and better shipping characteristics Terminator gene technology (suicide seeds)	Elimination of genes for toxic or allergenic substances Suppressed potato sprouting Reduction of pod shatter in oil seed rape White clover & alfalfa with more tannin to control bloat
Introduction of new genes or enhancement of existing gene action for enhancing and amending flavour or colour, or modify starch and oil content	Pre-coloured flowers (e.g. mauve and black carnations in Australia) High-lauric acid oil seed rape (USA: no longer being grown)	Trees with modified lignin content Pre-coloured cotton (blue) Oil seed rape with disease resistance and oil modifications Maize modified for high lysine or high oils (for animal feed)	Crops for industrial oils/plastics Modification of maize for high wax (99% amylopectin: for starch manufacture) or for high amylose (>50%: for wet milling and industrial use) Modifications to increase efficiency of nutrient, water and light use (hormone changes to affect grain filling, or delay of leaf ageing) Better cotton and tree fibre quality Legumes and oats with increased protein and energy
Introduction of new genes for enhancing nutritional content of crop (nutraceuticals) or pharmaceutical content of crop or animal	No nutraceuticals Alpha-antitrypsin rice (USA only)	Vitamin A rice (golden rice) Iron-rich rice Forage legumes with increased sulphur content Sheep and pigs modified to produce human proteins in their milk, such as insulin, interferon, and the human blood clotting protein factor 8	Vaccine crops (e.g. banana and potato) containing genetic material from pathogens that work as vaccines when eaten (e.g. potato-based vaccine against hepatitis B) Forage grasses with lowered lignin levels and/or changes in enzymes, so more nutritious to livestock fresh and as silage
Introduction of genes for enhancing resistance to herbicides, pests and pathogens	Herbicide-tolerant (HT) soya and oil seed rape (canola) Bt maize and cotton Bt + HT cotton ('2-gene cotton') Potato resistant to Colorado Beetle (USA) HT chicory (Netherlands) Viral-resistant papaya (Hawaii)	HT sugar beet Bt clover (New Zealand) Viral resistance in rice, pepper, tomato, cassava, sweet potato Cereals resistant to storage pests Nematode resistance in cereals, banana, potato	Use of highly-specific toxins from scorpion, wasp, funnel spider and cone snail Trees with pest/disease resistance Potato and vegetables resistant to fungal pathogens and pests Sunflower resistant to diseases
Introduction of genes for enhancing resistance to environmental stresses	None	Frost-tolerant strawberry Tolerance to Al toxicity through secretion of citric acid by roots Salt-tolerant mustard HT, fungal resistant and stress tolerance (salt, heat) in turf grass	Frost tolerance in beet and potato Isolation of drought-, thermo-, salt-, and metal-tolerance complexes Rice tolerant of submergence
Introduction of genes for modifying the environment	Bacteria in containment systems for production of enzymes for cheese and washing powder	Modified bacteria for bioremediation of soils	Improved N-use efficiency in potatoes, wheat and grasses Grasses for soil remediation
Introduction of genes to enhance production of hybrids or to modify seed production by inducing apomixis (so fixing hybrid vigour and allowing farmers to save seed)	None	Apomictic maize	Apomixis in wider number of crops and forage grasses
Adjusting switching mechanisms through promoters to turn on and off traits	None	Gene use restriction technology (GURT) or 'terminator'	Switching mechanisms to turn on DNA when selected disease or climatic conditions prevail

DETR 1999). Pollination is not the same as gene flow; though pollen can travel many kilometres, it will only rarely result in a pollination event (McPartlan & Dale 1994; Gray & Raybould 1998; BCPC 1999; Young *et al.* 1999; ACRE 2000*b*). Furthermore, many GM lines are male sterile, so even though pollen transfer may occur, pollination cannot. A further concern is the potential for uptake of transgenic DNA by soil bacteria, which is referred to as horizontal gene flow (Gebhard & Smalla 1998, 1999; ACRE 2000*b*).

In the UK, oil seed rape (OSR) is a possible candidate for gene flow, as it has many weedy relatives. Concerns centre on the possibility of transfer of HT from GM-OSR to weeds, leading to the emergence of 'superweeds' resistant to herbicides. However, several years of research investigating both manual and spontaneous crossing indicates that OSR has low probability of gene flow to wild relatives (Mikkelsen *et al.* 1996; DETR 1999). However, the fitness of individual plants, and the rates of gene spread will depend upon the selection pressures exerted on the HT gene of interest, a gene that is unlikely to confer a selective advantage in the wild. By contrast, sugar beet, carrot, ryegrass and white clover all have a 'high-probability' of gene flow, as wild relatives are effectively the same species as the crop. There is minimal probability of gene flow for potato, maize and tomato, as they have no compatible wild relatives in UK (Raybould & Gray 1993; DETR 1999; Young *et al.* 1999). The risks will, therefore, change from country to country, with, for example, GM maize becoming more of a potential risk in Mexico, the centre of origin for maize itself.

The important question is not so much whether gene flow occurs, but rather to what extent transgenes might affect native plant ecology. As Johnson (2000) put it: 'To add genes from other plants unwittingly and randomly to native gene pools may result in phenotypic effects which could change the way entire genomes relate to their physical and biotic environments'. Thus, the transfer of transgenes designed to prevent germination would lower fitness of new crop-native hybrids, whereas resistance to insects, fungi and viruses could substantially increase fitness. This could lead to the emergence of weeds with multiple-stacked genes for herbicide tolerance.

Emergence of new forms of resistance and secondary pest and weed problems

The second environmental risk centres on the potential for emergence of new forms of resistance and/or secondary pests and weeds. Resistance had already emerged on a very large scale in modern agriculture before the emergence of GMOs (Georghiou 1986), and there are now 500 species of insect, mite or tick resistant to one or more compounds, together with more than 400 herbicide-resistant weed biotypes, and 150 resistant fungi and bacteria (Vorley & Keeney 1998; Heap 2000).

Evolution of resistance can occur in the context of (1) GM crops expressing an insecticidal product (e.g. *Bt*), leading to insect resistance, or (2) GM crops leading to overuse of herbicides, leading to weed resistance. At first, the potential problem of insect resistance, particularly in *Bt* maize and cotton, went unrecognized. Now, though, there are mandatory rules where GM crops are grown on a large scale to reduce the selection pressure on pests. The EPA (1999) and USDA (1999) have set out guidance for integrated resistance management (IRM) for *Bt* GM crops (maize, cotton and potato), which includes three strategies: (1) a proportion of the cropped area must be devoted to refuges of non-GM crops; (2) use of rotations, especially soya beans with maize; and (3) reduced use of *Bt* maize where growers do not need it (e.g. where corn-borer pressure is low).

The guidance indicates that 20% of farmland must be devoted to refuges within 0.8 km (preferably 0.4 km) of a *Bt* maize, potato or cotton field, with varying rules for refuge size depending on the proportion of a parish under the same GM crop. For *Bt* maize grown in a cotton area, the stipulation is a 50% non-*Bt* maize refuge within 0.4 km (so as to minimize corn earworm and cotton bollworm resistance). The aim is to provide sufficient susceptible adult insects to mate with potential *Bt*-resistant adult insects to dilute frequency of resistance genes. However, there is still controversy over the size, structure and deployment of non-*Bt* crop refuges, how they should be implemented at a regional scale, and the difficulty of enforcing or encouraging farmers to adopt them.

GM crops themselves may also become problem weeds in the rotation, such as HT and *Bt* cotton germinating in the following soya crop, or volunteer HT OSR in following cereals. If the following crops were to be treated with the same herbicide, then this would be ineffective. However, such volunteers can be eliminated with alternative products, controlled with cultivation, or choice of smothering crop.

New secondary pest problems can also arise, such as in cotton (Bachelor 2000). In 1999, researchers compared 360 paired fields of GM and non-GM cotton in South Carolina. The GM fields had 41% less total insect damage (1.6% of bolls compared with 3.9%), but stink bug damage was four times higher (2.6% compared with 0.6%). Stink bug damage has also been noted in Georgia (Hollis 2000), but there were greater levels of beneficial insects in GM fields, and total boll damage was lower.

Recombination of viruses and bacteria to produce new pathogens

A third risk relates to the potential for viruses or bacteria to incorporate transgenes into their genomes, leading to the expression of novel and possibly undesirable traits. Additionally, viral transgenes incorporated into the GM crop could recombine to produce viruses with high fitness. However, such recombination has not yet been shown to occur (Royal Society 1998). In theory, viral genes could affect humans too, by surviving passage through the human gut and entering gut bacteria and human body cells. Once inside cells, DNA could insert itself into the genome to change the basic structure and functions. This could lead to the emergence of new diseases. However, this would need the integration of whole sequences of DNA into the human genome, a highly unlikely event given current knowledge.

Direct and indirect effects of novel toxins

The fourth risk centres on the potential direct and indirect effects of novel toxins expressed by GMOs. *Bt* is expressed by all cells in a *Bt* maize or cotton plant, and so could affect either beneficial organisms coming into direct contact with the plant or plant products, or indirectly through consumption of a herbivorous insect that has sequestered the toxin in its tissue. In laboratory conditions, several potential risks have been demonstrated, such as of *Bt* pollen on Monarch butterflies (Losey *et al.* 1999), of GM potatoes expressing a lectin, *Bt* maize affecting ladybirds (Coccinellidae) and lacewings (Chrysopidae) (Birch *et al.* 1997; Hilbeck *et al.* 1998), and of *Bt* products in the soil (Crecchio & Stotzky 1998; Saxena *et al.* 1999). However, these laboratory studies do not necessarily mean a real risk arises in the field.

A good example of the difficulties is represented by recent studies of the effect of pollen from GM maize on Monarch butterflies (*Danaus plexippus*; Losey *et al.* 1999). The larvae of Monarchs were reared in laboratories on milkweed leaves dusted with *Bt* maize pollen, and these larvae ate less, grew more slowly and had higher mortality than those reared on leaves dusted with non-GM pollen. The potential threat to a nationally important species raised great concerns about GMOs in general, despite the fact that *Bt* is known to be toxic to Lepidoptera. However, the dose of pollen required to cause an effect in the field, the amount of pollen on milkweed leaves, the likelihood of butterflies being exposed to pollen, and the photodegradation of *Bt* and rain-washing effects all remain unknown.

For Monarchs, timing is vital. For harm to occur, the larvae have to emerge at the same time as maize is pollinating, a narrow period of 7–10 days. However, Monarch migration and *Bt* pollen show do not coincide, pollen does not travel far (90% falls in the first 5m), larvae on milkweed are not adversely affected by *Bt* pollen, and most milkweed tends not to be found close to maize fields (Monarch Butterfly Research Symposium 1999; Jesse & Obrycki 2000). Again, this does not mean to say that all potential risks from *Bt* crops will be shown to be small, just that a detailed understanding of the context of the cropped environment is needed before a judgement about risk can be made.

Changes to farm practices leading to changes in biodiversity

Because of the incorporation of GMOs into their farm practices, farmers may also contribute directly or indirectly to biodiversity losses. The primary concern centres on the adoption of HT crops that result in the increased use of broad-spectrum herbicides. Such products offer the option of a 'complete weed-kill', which is good for the crops, but particularly bad for farmland plants, mammals and birds (ACRE 1998; Royal Society 1998; Johnson 2000). The trend towards clean fields with no weeds, and thus no herbivorous insects or seed production (which in turn comprise food for birds and mammals) has been a major factor in the decline of farmland birds (Campbell *et al.* 1997; Pretty 1998; Siriwardena *et al.* 1998; Mason 1998).

Once again, however, much depends on the detailed agronomy and goals of farmers. Some GMOs could lead to greater biodiversity: according to research at IACR-Brooms Barn, input costs are down from £200 to £30 per ha per year for glyphosate-tolerant sugar beet (not counting the company technology fee), with farmers able to leave weed control until at least the four-leaf stage, which makes beet plants harder for aphids to find and encourages beneficial predators (Dewar *et al.* 2000). This precise control of weeds at the time when they pose a real threat to yields could also give the option of greater tolerance of weeds at other times, so leading to biodiversity benefits (Johnson 2000). At the same time, HT (glufosinate ammonium tolerant) sugar beet has been shown to allow virtually complete removal of all weeds using less herbicide than a conventional crop would require (Read & Bush 1999). In the USA, detailed comparative studies have shown that, in some circumstances, farmers with HT soya beans are indeed using more herbicide than conventional growers (Benbrook 1999).

Potential human health risks

Allergenic and immune system reactions to new substances

As transgenes result in the manufacture of new products in crops, usually proteins, a risk to humans arises if these products provoke an additional allergenic or immune response. Conventional non-GM foods already contain a large number of toxic and potentially toxic products, and so the key question is whether a specific GMO could result in a new hazard. As some 90% of food allergens occur in response to proteins found in eight foods (peanuts, tree nuts, milk, egg, soya bean, shellfish, fish and wheat), it could be argued that as GM involves transfer of a single or few genes, so it is easier to test for allergenicity (Royal Society 1998). One product, GM soya with a Brazil nut gene, has been withdrawn from development because of potential allergenic effects (Nuffield Council on Bioethics 1999).

The greatest controversy has surrounded the case of GM potatoes containing lectin and their effect on rats. Immune response effects have been claimed (Anon. 1999), but the research has been widely criticized (see Nuffield Council on Bioethics 1999 for summary). If the research had indeed shown an effect, then this would be significant only for this particular gene and its product. Equally, though, the absence of effect does not mean that all GMOs are safe. Other potential problems might arise in potatoes with modified biochemical pathways that could inadvertently lead to increased levels of glycoalkaloids. It is also important to distinguish between consumption of food products potentially containing GM DNA, and food products that are identical to those from conventional crops, such as refined sugar.

Antibiotic resistance marker genes

The first-generation GMOs have used antibiotic or herbicide marker genes for easy cellular selection. In theory, antibiotic-resistant marker genes from a GMO could be incorporated into bacteria in the guts of humans and livestock, so rendering them also resistant to the antibiotic (Gassen 2000). Although this has not yet been demonstrated empirically, antibiotic resistance is still a major cause for concern. Antibiotics and other antimicrobials are used in agriculture for therapeutic treatment of clinical diseases (20%), and prophylactic use and growth promotion (80% of total). Concern is growing that overuse of antibiotics may render some human drugs ineffective and/or make some strains of bacteria untreatable. The World Health Organization has documented direct evidence that antimicrobial use in farm livestock has resulted in the emergence of resistant *Salmonella, Campylobacter,* Enterococci, *E. coli* types, and vancomycin-resistant enterococci are linked to the overuse of antibiotics both in hospitals and on farms (House of Lords Select Committee on the European Communities 1998).

Alternatives to antibiotic markers now exist, and many believe antibiotics should not be used in commercial GMOs (British Medical Association 1999; ACRE 2000*b*). The Royal Society (1998) said: 'It is no longer acceptable to have antibiotic resistance genes present in a new GM crop'. Nonetheless, it is still not clear whether antibiotic marker genes add significantly to the risk of resistance emerging from exposure to antibiotics used elsewhere in the food chain.

The contrasting concerns of different stakeholders

The pace of change in the development of GM technologies has provoked many contested debates, some specifically about the benefits and risks of GM technologies. Others, though, are about important indirect effects, such as the growing centralization of world agriculture, that represent structural changes in agriculture in which GMOs are a contributor to change, but not necessarily the driver. A selection of questions relating to these contested positions follows.

(1) Will GMOs continue to promote purely technological approaches to modern agriculture, or could such technologies bring great environmental benefits, and promote sustainability?
(2) Are GM technologies essential for feeding a hungry world, or is hunger more a result of poverty, with poor consumers and farmers unable to afford modern, expensive technologies?
(3) Does genetic modification across species represents a breakdown of natural species barriers, or does the presence of common gene sequences across very different species indicate that such transfers are straightforward and of little novel concern?
(4) Are GMOs 'substantially' equivalent' to other foods, and so not require labelling, or is labelling a right for consumers as it permits them to make informed choices?
(5) Will GMOs contribute to greater consolidation of corporate power in the food system, and, even if they do, are such globalized operations a necessary and desirable part of economic growth?

All of this has brought great confusion, and a tendency for the protagonists to dismiss the concerns of environmental or consumer groups as misguided, but without realizing the complex of concerns that people have when scientists make promises about new technologies (US Senate Science Committee 2000). Equally, those against GMOs too readily dismiss the pro-lobby as unbalanced in presentation and unable properly to assess the risks (Grove-White *et al.* 1997; ESRC 1999).

A significant danger is that scientists, together with farmers who produce the food, will further lose the trust of citizens. Mary Shelley's Dr Frankenstein is condemned not so much for what he wanted to achieve, even though it may have been flawed, but because he fails to take responsibility for his actions (Shelley 1818). The creature, popularly but incorrectly called 'Frankenstein', does not engage in gratuitous violence. He takes revenge when the scientist, Frankenstein, refuses to create another creature to overcome his loneliness. It is such a lack of responsibility and trust that could irreparably damage the science of GM. Many food manufacturers and retailers have banned GM products from their foods. Many farmers are uncertain: they would like access to technologies that may give competitors an advantage, but equally would not like further to lose the trust of consumers (Royal Society 1998).

However, there is much that can be done to engage wider groups of stakeholders in constructive debate and discussion, and to ensure the adoption of a more precautionary stance to new technologies (ESRC 1999; O'Riordan 1999).

(1) Where unambiguous scientific proof of cause and effect is not available, then act with a duty of care.
(2) Where the benefits of early action are judged greater than the likely costs of delay, it is appropriate to take a lead and to inform why such action is being taken.
(3) Where there is the possibility of irreversible damage to natural life support functions, precautionary action should be taken irrespective of the foregone benefits.
(4) Always listen to calls for a change of course, incorporate representatives of such call into deliberative forums, and maintain transparency throughout.
(5) Never shy away from publicity and never try to suppress information, however unpalatable. In the age of the internet, someone is bound to find out if information is being distorted or hidden.
(6) Where there is public unease, act decisively to respond to that unease by introducing extensive discussions and deliberative techniques.

Not all agree, however, on the value of deliberative processes involving larger numbers of stakeholders. The US Senate Science Committee (2000) adopted a highly combative tone in reporting on GMOs in the USA. It was dismissive of 'political activists', indicating that critics of GM had 'mounted well-funded campaigns' (as if it was unfair that they should be well-funded). It also said that 'The US should not accept any international agreements that endorse the precautionary principle'. It is unlikely that this continuing dismissal, on both sides, will lead to constructive outcomes.

GM as another technological fix or as contributor to sustainability?

A long-contested debate centres on the potential for GMOs to contribute to greater sustainability in agriculture. The issue is multi-layered and depends fundamentally on the comparators and practices that GM technology would replace. For example, a GM technology resulting in reduced use of pesticides could be more sustainable than a conventional system relying on pesticides, but this GM/reduced-use system would score less well if compared with an organic system that used no pesticides.

Many commentators have argued that GM technology represents no more than a further technological fix on an intense agricultural treadmill. Modern agriculture has been highly successful at increasing food production, but it has also brought costly environmental and social consequences (Pretty *et al.* 2000). Solving these problems has often meant treating the symptoms rather than the underlying problems (Kloppenburg & Burrows 1996; Altieri & Rosset 1999*a*).

In this process of technological determinism, problems are seen as solvable with new technologies, in which the tendency is to address symptoms rather than underlying problems. Kloppenburg & Burrows (1996) point specifically to the case of GM potatoes containing a toxin against Colorado Beetle: 'Monsanto has constructed the problem as the potato beetle, not as potato monoculture'. Altieri (1998) makes a similar point: 'biotechnology is being pursued to patch-up the problems caused by previous agrochemical technologies (pesticide resistance, pollution, soil degradation) which were promoted by the same companies now leading the bio-revolution'.

The question of the preferred approach, either fundamental redesign of agriculture, or a modernist agriculture with increasing eco-efficiency (cf. MacRae *et al.* 1993; Pretty 1998), cannot be resolved here as it depends upon constructions of what is a more sustainable agriculture, and whether GM can be made to work for sustainability outcomes (Pretty 1995, 2000*b*; Altieri 1996, 1999; Conway 1997). To what extent, then, are commercially cultivated GMOs currently helping to make this a transition towards sustainability? Four aspects of the data require investigation: (1) increasing yield claims; (2) reduced insecticide claims; (3) reduced herbicide claims; and (4) secondary problems arising from monocultures of GMOs.

It is important to note that commercially-cultivated GMOs are not alike in their outcomes, despite the compelling narrative that GMOs will both increase yields and reduce agrochemical use (US Senate Science Committee 2000). Unconditional claims by companies, or by industry-funded research, have fostered further questions about the efficiency of GM technologies (Gianessi & Carpenter 1999). For every company press release or aligned-report that indicates substantial yield and environmental benefits, there is another report that suggests problems with the technology. It is impossible to draw any firm conclusions from either side.

Well-designed and independent research takes longer to conduct and write-up, and it is only recently reports on field-based evidence have appeared. Research from the Universities of Arkansas, Missouri, Nebraska, Ohio State, Purdue, and Wisconsin in 1999–2000, together with some reports from United States Department of Agriculture (USDA) and Environmental Protection Agency (EPA), indicate a highly mixed performance in the field, including some agronomic surprises (Benbrook 1999; ERS-USDA 1999*a*; Minor *et al.* 1999; National Corn Growers Association 1999; Oplinger *et al.* 1999; USDA 1999; Conway 2000; Elmore *et al.* 2001*a*, *b*; Hyde *et al.* 2000; H. Willson, personal communication 2000). This literature does not support the US Senate Science Committee's (2000) contention that 'the current generation of pest-resistant and herbicide-tolerant agricultural plants produced by biotechnology has reduced chemical inputs and improved yields'.

Yields

There is widespread consensus that yields have not increased, rather they have tended to be lower compared with conventional varieties (Elmore *et al.* 2001*a*, *b*). Nebraska University's comparative study of HT and conventional soya beans (1998–1999) found that HT yielded 6% less (200 kg/ha) than their closest relations and 11% less than high-yield conventional soya beans. Researchers distinguished between two problems: yield drag, arising from problems relating to the transgene or insertion itself, and yield lag, arising from the type of soya beans into which the transgene had been inserted (the yield potential of conventional varieties may have overtaken that of an older GM variety). Benbrook's (1999) study of 8200 university-based varietal trials in 1998 found a similar yield drag of 5–7% for GM varieties, with 'the best conventional variety producing yields on average 10% or more higher than comparable Roundup Ready™ varieties sold by the same seed companies'.

Yields of cotton appear largely unchanged at most locations (ERS-USDA 1999*a*), and those of maize are mostly unchanged (in 12 out of 18 regions), except where there has been high corn-borer pressure. Where pressure was high, yields were 5–30% greater for GM maize (ERS-USDA 1999*b*). In Missouri, however, no significant differences in yield under various corn-borer pressures across the state were found (Minor *et al.* 1999), and at the University of

Purdue it has been concluded that farmers may not benefit by adopting *Bt* technologies under average pest infestation levels, given that economically-significant pest attack occurs only one in 4–8 years in most locations in the USA (Hyde *et al.* 2000).

Insecticide use

Insecticide use appears generally to be down, particularly in cotton, where there are also significant increases in beneficial insects in the crop. Most commentators report significant reductions in numbers of sprays per hectare per year, resulting in a cut in national insecticide use of 450 000 kg active ingredient (ai). This represents a reduction of just 0.18 kg ai/ha, or 9% of the average application of 2.01 kg ai/ha (ERS-USDA 1999*a*). Similarly impressive aggregate savings in insecticide use for maize also look less significant on a per hectare basis, a saving in 1998 of 320 000 kg ai translating to a reduction of just 0.04–0.08 kg ai per hectare. Much larger reductions in per ha insecticide use have been achieved by farmers using integrated pest management methods in both the tropics and temperate regions (Pretty 1998; Pretty & Hine 2000).

For maize, some national agencies indicate large decreases in use, but the USDA's own National Agricultural Statistics Service (USDA 1999) has recorded that the majority of maize insecticide is applied at pre-emergence stage for control of corn rootworms, cutworms and other soil insects: 'there has been little change in insecticide use, despite the planting of millions of acres of *Bt* corn in recent years'. Data submitted to the US Environmental Protection Agency by the National Corn Growers Association (1999) showed that in the USA the proportion of the maize crop sprayed against corn borers (the target of *Bt* maize) increased by 45% in the first two years of *Bt* maize use (1996–1997; though this may be partly due to increased awareness of the corn-borer problem, variation in pest numbers, and improved scouting).

Herbicide use

Unlike use of insecticides, that of herbicides appears to have increased (Benbrook 1999). HT OSR and soya should mean reduced herbicide use. Again, it is what happens in the field that determines the real risks. The complexity of weed treatment means that herbicide use on these GM crops appears to be on the increase. Farmers are faced with three choices: (1) let the weeds grow to a size that allows a complete kill on spraying, but which means yields suffer owing to competition from the weeds; (2) use a pre-emergence herbicide plus the broad-spectrum product; or (3) apply the broad-spectrum product at least twice. It is increasingly reported that farmers are resorting to both the latter two options, meaning that these GM crops are actually leading to increased herbicide use. This is a very different picture to that painted by personal testimony to the US Senate Science Committee (2000, p. 29), when one scientist indicated that the use of Roundup Ready™ soya beans had 'saved farmers nearly US$ 30/ha because of a 40% reduction in herbicide usage, and also increased crop yield due to less competition from weeds'.

Secondary problems

There are also secondary problems arising from a wide shift to a single new technology, mostly bringing new agronomic problems for farmers, not environmental risks. These include emerging (1) resistance to pests; (2) weed shift problems (e.g. emergence of tolerance amongst weed species to glyphosate); (3) pest shift problems; and (4) crop volunteers developing problems in rotations (Bachelor 2000). Such agronomic problems are exacerbated when farmers do the same thing year after year, both in terms of crop rotations and herbicide choice.

GM as driver of corporate power or as friend of farmers?

Another contested issue relates to the rapidly changing structure of world agriculture, especially the vertical integration of corporations, and the growing concentration at every stage of the food chain. Throughout world agriculture, there are fewer input suppliers, fewer farms, fewer millers, slaughterers and packing businesses, and fewer processors. Such vertical integration is a concern to many. The UK House of Lords Select Committee on the European Communities (1998) stated: 'There is a concern, shared by farmers, witnesses and ourselves, that the powers of a few agrochemical/seed companies are already great, and will become greater, over the process of producing (developing and growing) GM crops'.

As GMOs are being commercially produced by many of these same large corporations, there is intense interest in how power relations and property rights will play out (Hubbell & Welsh 1998; Herdt 1999). Important questions arise: to what extent are these private interests concerned only with their shareholders' gain, or are they willing to engage with farmers of all types, both in industrialized and developing countries?

A critical issue relates to who gets (or owns) the benefits of the new technology. Patent law is vital, as it treats genes and genetic engineering in the same way as any other invention. To be patented in Europe, as covered by the European Convention, an invention must be 'new', 'not obvious', 'capable of industrial application', and 'patentable subject matter'. To be considered new, an invention must add to the current state of knowledge: a new method of isolating a gene qualifies, as does an isolated gene with a new activity. A gene in a human body does not qualify. It is possible, however, to patent an artificially synthesized gene or the replication of the genetic information contained in the gene. It is not the original gene, but said to be just a good copy.

Also important is the international Convention on Biological Diversity (CBD). It came into force on 29 December 1993, and has three stated objectives, namely the conservation of biological diversity, the sustainable use of its

Table 2 Comparison of GM and conventional cotton costs in North Carolina, 1999 (Bachelor 2000).

	GM cotton	*Conventional cotton*
Total boll damage (%)	4.47%	5.25%
Bollworm damage	1.61%	3.93%
Stink bug damage	2.58%	0.61%
Insecticide use	0.75 applications	2.53 applications
Total costs to farmer (US$/ha)	67.40	61.90
Technology fee to company	47.30	0.00
For insecticides	13.90	46.90
Lost cotton and scouting fees	6.00	15.00

components, and the fair and equitable sharing of the benefits coming out of the use of genetic resources. Plant genetic resources are economically valuable, as they are the basic building blocks for the biotechnology industry. However, it is difficult to allocate 'ownership' when so many genes interact in highly complex ways to express characteristics. The conventional wheat variety, Veery, for example, was the product of 3170 different crosses involving parents from 26 countries. Under the CBD, the country of origin and the legal owner of plant genetic resources is legally defined as the first to file a claim on ownership, but it is very difficult to attribute clear ownership when a variety clearly comes from so many sources (Fowler & Mooney 1990).

At the farm level, reduced use of insecticides, combined with increased yields, should mean greater benefits for farmers. Companies, however, charge a technology fee (on top of seed costs), and to date this appears to capture most or the entire margin in certain systems (Table 2). However, if the GMO fails to deliver promised benefits to farmers, corporate-farmer relations can begin to fail. In 1998, 55 Mississippi farmers complained to their state Department of Agriculture and Commerce's arbitration council because their GM cotton had lower yields or had completely failed. Most settled out of court; three were awarded US$ 1.9 million in damages. In 1999, 200 cotton farmers from Georgia, Florida and North Carolina were engaged in legal dispute with Monsanto after crop failure of *Bt* and HT cotton.

There are signs, however, that some corporations are taking a new path in developing benefit-sharing mechanisms. A ground-breaking arrangement between AstraZeneca (now Syngenta) and the inventors of Vitamin-A rice (golden rice; Potrykus 1999) will permit farmers in developing countries to earn up to US$ 10 000 without paying royalties. The deal permits the company to commercialize the rice, whilst effectively providing it free to small farmers. There remain, however, many controversies over 'golden rice', including whether vitamin A deficiency could better be addressed through diversified diets, and the cultural resistance to eating orange rice. Another example is the Positech™ selection technique, an alternative to antibiotic resistant markers. Developed by Novartis (also now Syngenta) at a cost of US$ 10 million, the company has said it will market Positech™ under a two-tier pricing system, with commercial uses incurring royalties, while those developing technologies for subsistence farmers will be granted free access. However, this may also mean that public researchers will be prevented from using such technologies owing to their high price.

GM as feeder of the world or eliminator of alternatives?

A further contested debate centres on whether GM crops could help to feed the world. Some say emphatically yes, often raising the spectre of famine as a way to gain greater support for GM technologies as a whole (cf. McGloughlin 1999), but GM technologies can only help to feed the world if attention is paid to the processes of technology development, benefit sharing, and more especially to alternative or low-cost methods of production. Most commentators agree that food production will have to increase, and that this will have to come from existing farmland. However, past approaches to modern agricultural development have not been sufficiently successful in many parts of the world. In Africa, for example, per caput food production has fallen by about 20% since the mid-1960s. At the aggregate level, the world produces enough food to feed everyone with a nutritious and adequate diet (some 354 kg of cereal per person per year), yet there are still some 790 million people in serious food insecurity (Pinstrup-Andersen *et al.* 1999; FAO 2000; Smil 2000; Pretty & Hine 2001).

In most cases, people are hungry because they are poor. They simply do not have the money to buy the food they need. Poor farmers (and poor countries) cannot afford expensive 'modern' technologies that could theoretically increase their yields. What they need are readily available and cheap means to improve their farm productivity (Altieri & Rosset 1999*a*, *b*). Therefore, a cereal crop engineered to have bacteria on the roots to fix free nitrogen from the air, or another with apomixis, would be a tremendous benefit for poor farmers, but unless this technology is cheap, it is unlikely to be accessible to the people who need it most.

Sustainable agriculture is now an increasingly viable option for developing country farmers (Pretty 1995; Altieri 1996; Conway 1997; Rosset 1999; Pretty & Hine 2000). It integrates agro-ecological processes such as nutrient cycling, nitrogen fixation, soil regeneration and natural enemies of pests into food production processes, and minimizes the use of non-renewable inputs (pesticides and fertilizers) that damage the environment or harm the health of farmers and consumers. It makes better use of the knowledge and skills of farmers, so improving their self-reliance and capacities. Remarkably, the best evidence of 'success' comes from many poor countries of Africa, Asia and Latin America (Pretty 2000*c*; Pretty & Hine 2000, 2001). Regenerative technologies and practices can be beneficial for both farmers and rural environments, particularly where they have the security of tenure to improve natural assets. This evidence suggests substantial improvements in food production can occur through one or more of four mechanisms.

1. (1) Intensification of a single component of a farm system (with little change to the rest of the farm), such as home garden intensification with vegetables and/or tree crops, vegetables on rice bunds, and introduction of fishponds or a dairy cow.
2. (2) Addition of a new productive element to a farm system, such as fish or shrimps in paddy rice, or agroforestry, which provides a boost to total farm food production and/or income, but which does not necessarily affect cereal productivity.
3. (3) Better use of natural capital to increase total farm production, especially water (by water harvesting and irrigation scheduling), and land (by reclamation of degraded land), so leading to additional new dryland crops and/or increased supply of additional water for irrigated crops (so increasing cropping intensity).
4. (4) Improvements in per hectare yields of staples through introduction of new regenerative elements into farm systems (e.g. legumes, integrated pest management) or through introduction of new and locally appropriate crop varieties and animal breeds. Although starting from a lower base, these yield increases are greater in rain-fed systems than in irrigated ones. Typical improvements in rain-fed systems are 50–100%, rising to 200% (a tripling of yields) in certain circumstances, and in irrigated systems some 5–10%, rising to 30% when whole crop management is addressed.

Where there are no alternatives, then GM technologies are likely to represent novel and effective options (CGIAR 2000; Royal Society *et al.* 2000; Winrock International 2000). If research is conducted by public-interest bodies, such as universities or non-government organizations, whose concern is to produce public goods, then biotechnology could result in the spread of technologies that have immense benefits. Research underway already includes that focused on: the development of virus-resistant cassava, potatoes, sweet potatoes and maize; micro-propagation of multipurpose trees; on nematode-resistant bananas; thermo-tolerant and drought-tolerant pearl millet; virus and nematode resistance in rice; *Striga*-resistant maize; and pest-resistant wheat (Tanksley & McCouch 1997; DFID 1998; ISAAA 2000).

One example is rice yellow mottle virus, which is a major factor limiting African rice production, commonly reducing yields by 50–95% (Pinto *et al.* 1998). It has not been possible to introduce resistance to local varieties through conventional breeding, but GM has led to the development of novel resistant varieties. These have been tested in five countries, with resultant complete resistance to the virus.

Another example is tolerance to salinity. Soil salinity is thought to affect some 340 million hectares worldwide. Some plants are known to produce and accumulate osmoprotectant solutes (e.g. glycinebetamine, mannitol, trehalose and proline). These non-toxic solutes can accumulate to osmotically significant levels to protect against damage from high salt concentrations in the soil. Introductions of single genes have led to modest accumulations of solutes, but to be successful, multiple genes coding for entirely new metabolic pathways will be needed (Royal Society *et al.* 2000). Further GM applications could improve yields in developing countries: if they remove or tolerate a stress (e.g. rice tolerating prolonged submergence); if they allow cultivation of problem soils (e.g. aluminium toxicity); or if they give yield a boost (e.g. genes from wild rice in China into best performing hybrids raised yields by 20–40%; Conway 1997).

Nonetheless, new threats to the livelihoods of developing country farmers may yet arise. Transgenic tropical crops such as sugar cane, oil palm, coconut, vanilla and cocoa could be grown anywhere with appropriate genetic modification. Other crops may be engineered to replace tropical products: oil seed rape, for example, could be engineered to produce lauric acid for soap making, so putting out of business producers of oil palm in Malaysia and Ghana.

New policy directions

GMOs are not a single, homogenous technology. Each application brings different potential benefits and risks for different stakeholders. Regulators, therefore, face special challenges in the face of rapidly developing technical applications. In the European Union, releases of GMOs were regulated under Directive 90/220 for a decade. Following protracted negotiations, this has now been revised, harmonized and tightened, and signed into effect in early 2001. Directive 2001/18/EC sets out provisions for scientific assessment of the risks of experimental and commercial releases of GMOs into the environment, as well as establishing protocols for rigorous post-release monitoring.

The novel nature of this emerging policy centres on a fundamental shift in risk assessment to a need to understand the effects of technologies in the field and on the farm. To date, the general approach in agriculture as a whole has been to establish rigorous risk assessment procedures prior to release, but then to assume farmers engage in 'good agricultural practice'. Much of the harm to environment arises when technologies, whether pesticides, fertilizers or machinery, are not used in accordance with regulators' criteria. The assessment of GMOs, however, will now contain new requirements to assess the effects of diverse farm practices on GMOs themselves, and how this interaction will affect desirable environmental outcomes, such as integrity of local biodiversity. This could have a significant effect on agricultural-environment interactions in non-GM components of agricultural systems.

However, these standards for regulation are not yet widespread. The challenge that developing countries face is to find ways to increase regulatory and scientific capacity to assess the effects of modern agricultural technology on their environments. The Convention on Biological Diversity establishes a broad framework for assessing effects, and efforts are underway to see the January 2000 agreement by 130 countries to adopt the precautionary principle as the basis for an International Biosafety Protocol signed and put into practice (Juma & Gupta 1999). The centre-piece could be an advance informed agreement procedure to be followed before transboundary transfer of GMOs, though a bloc of agricultural exporting nations still argue that agricultural commodities should be excluded from this procedure.

Whether such international agreements can be signed or not, there is still a high priority on findings ways to help build domestic scientific and legal capacity within countries to establish comprehensive biosafety protocols for GMOs (Pinstrup-Andersen 1999). Such a comprehensive policy framework will need to protect intellectual property rights, to protect against environmental and health risks, and to regulate the private sector through appropriate anti-trust institutions if developing countries are significantly to benefit from GM technologies.

Conclusions

The pace of change in agricultural biotechnology poses important challenges for both risk and benefit assessment, and for the development of effective policies for risk reduction. Evidence from the field suggests that some GMOs offer opportunities for environmental improvements, though indirect effects may be limiting these or even leading to the emergence of new problems. This strongly implies that each agricultural application of genetic modification must be assessed on a case-by-case basis drawing upon substantial understanding of the receiving environments if the best is to be made of these emerging technologies. This has important consequences for agricultural policies.

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