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The Environmental Impact of Genetically Engineered Crops

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Introduction

Scientific investigations on the safety and environmental impact of genetically engineered plants have focussed most intensively on issues relating to their interactions with other plants and animals that occur close to their site of cultivation (Connett and Barfoot, 1992; Casper and Landsmann, 1992). Important issues in this context include the potential for gene transfer to non-genetically engineered conspecifics (Umbeck *et al.*, 1991; Skogsmyr, 1994) or to related wild species via hybridisation (Gregorius and Steiner, 1993; Kapteijns, 1993; Raybould and Gray, 1993; Wilson and Payne, 1994; Jørgensen and Andersen, 1994) ; the potential for transgenic crop plants to become weeds (Crawley *et al.*, 1993; Tomiuk and Loeschcke, 1993; Bartsch, Sukopp and Sukopp, 1993; Crawley and Brown, 1995) and the toxicity of such plants to non-pathogenic organisms (Thacker, 1993/94). The expression and stability of foreign genes (Meyer, 1993) and the current methodology for field safety testing (Dietz, 1993; Gabriel, 1993; Bazin and Lynch, 1994; Regal, 1994) have also been critically examined. For a thorough discussion of these issues the reader is directed to the excellent review by Rogers and Parkes (1995); they will not be revisited at length here.

The present review focusses on additional issues not dealt with in detail elsewhere and on some broader issues of ecological importance which are generally considered to be outside the scope of scientific reviews such as those of Rogers and Parkes (1995) and Tiedje *et al.* (1989). It examines environmental issues related to the commercial development of more effective breeding strategies in crop plants, issues related to genetic erosion in crop plant resources, the production of novel, high value industrial products in plants, the use of plants as remedial agents for environmental contamination and the extension of the climatic and soil tolerance of crop plant species. Assumptions made about the environmental impact of genetically engineered plants during a period when climate, and therefore agricultural ecosystems, are changing are also critically examined. In addition, this review examines the potential environmental consequences of the economic impact of genetically engineered crops in developing

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countries. In conclusion, the review raises issues related to the ways in which the environmental costs and benefits of crop plant genetic engineering are presented by the scientific community.

Extensive reference is made to secondary sources, including some popular or general scientific journals. This is intended to focus attention on the fact that such sources currently act as catalysts for the discussion and debate of wider environmental effects of biotechnology which are largely ignored both by many primary scientific publications and by many reviewers in biotechnology and molecular genetics journals.

Enabling technology for plant breeders: F_1 hybrids

Increase in crop yield is a primary objective of plant breeding but, due to the polygenic nature of yield determination, there is at present little scope for direct, predictable increase in crop yield by genetically manipulating any single genes in metabolic or developmental processes that contribute to overall yield. The induction of male sterility for the production of F_1 hybrids is the only reliable means currently available for raising crop yields by molecular biological means, exploiting the frequently observed but poorly understood phenomenon of heterosis. Yield increases of up to 30% have been observed in experimental wheat hybrids, when a 2%–3% annual increase in yields by conventional pedigree breeding methods is the norm. The yield increases often observed in F_1 hybrids may have an important part to play in raising food production levels, at a time when the pace of yield improvement in some major crops is becoming more difficult to maintain by alternative breeding methods (Holmes, 1993a).

The most far-reaching agricultural innovation in plant genetic engineering achieved to date has been the insertion of tissue-specific genes that create the potential for rapid development of F_1 hybrid technology in all sexually reproducing crops. The expression of the barnase and barstar genes into the anther tapetum (Mariani *et al.*, 1990, 1992) allows the reliable and rapid introduction of male sterility (and therefore the ability to produce F_1 hybrids) in species where natural sterility mechanisms such as cytoplasmic and nuclear male sterility and gametophytic or sporophytic self-incompatibility are rare or absent.

The commercial benefits to seed producers derived from a greater use of F_1 hybrid crop technology are very large (Busch *et al.*, 1991). Hybrid vigour and optimum uniformity make F_1 hybrids attractive to farmers but their benefits to plant breeding companies include:

- control over the parental genetic material (and thus prevention of copying by competitors), providing biological reinforcement of legal patents
- genetic segregation of seed produced by F_1 hybrids, thereby preventing farmers from saving seed and ensuring that new seeds must be obtained every year
- a breeding system that allows easy and rapid incorporation of transgenes into one or both parental lines, thus allowing rapid stepwise improvement of existing F_1 varieties with little or no disruption to their existing desirable characteristics.

These agricultural and commercial benefits do, however, create concern that a general switch to F_1 hybrid production, as has already occurred in several field vegetable crops where reliable sources of male sterility already exist, could accelerate the pace of genetic erosion and enhance the risk of disease pandemics through a further reduction in the range of genetic variability within crops.

F_1 hybrids currently represent the extreme example of the use of a small sample of germplasm within a crop for the production of varieties that are grown over extremely large areas. Future developments in F_1 hybrid technology include the possibility of transferring apomixis-inducing genes from *Brachiaria* into a wide range of F_1 crops in the Third World (de Páez, 1994). This would allow farmers to cut costs by saving true breeding, asexually derived seed from year to year but would further reinforce their dependence on a limited range of genotypes. The hazards of such reliance on a narrow genetic base are well known and are exemplified in the pandemic of *Helminthosporium maydis* which devasted the maize crop in the United States in 1970 (Ullstrup, 1972).

The use of F_1 hybrids as a vehicle for transgenes is commercially attractive but the risks involved must be recognised. Much of the cost of developing F_1 hybrid technology involves the search for a suitable source of male sterility (which has been resolved by the use of the linkage of barnase genes to tapetum-specific promoters) and the identification and testing of inbred lines with high combining ability, which produce heterotic hybrids. The latter process involves screening and discarding a large number of inbred parents in a search for very few superior genotypes; one estimate in the late 1940s showed that only about 60 useful inbred *Zea mais* lines were isolated from 100,000 inbreds screened (Kiesselback (cited in Simmonds, 1979). By the 1970s 70% of US hybrid maize plantings were based on half a dozen superior inbreds. Consequently, there is a strong commercial impetus to modify existing parental lines in improvement programmes, rather than return to an extensive screening programme in the search for new characteristics. Genetic engineering of existing inbred parents offers an ideal methodology for this stepwise improvement of existing F_1 varieties.

The environmental risks involved are obvious; production of major crops could come to depend on a few families of F_1 varieties, with members of each family differing in only a few characters. Such strategies are known to produce ideal selection systems for the evolution and rapid multiplication of new strains of pathogen. If this is to be avoided, reliance must be placed on (i) plant breeding companies anticipating and taking steps to avoid the problem (thus incurring additional production costs) (ii) the willingness of farmers to plant pest refugium of crops with a wider genetic base, thus relieving selection pressure on pathogens (Mallet and Porter, 1992; Holmes, 1993b). This strategy depends on the availability of surplus agricultural land on farms for planting refugium crops, a factor which must also be taken into account when considering the yield advantage per unit land area of F_1 hybrid crops (and any crops which are genetically engineered for monogenic pest resistance) (iii) agricultural legislation to regulate the use of crops with a narrow genetic base, which is only likely if (i) and (ii) fail disastrously.

In the absence of these measures, crop security will become more dependent on plant breeders' ability to locate new resistance genes to meet every new pathogen challenge, and to use these to transform F_1 varieties whose commercial life is likely to be shortened by the rapid evolution of new pests and diseases. This strategy, which is likely to intensify the problem of reciprocal selection between crops and pathogens, represents a reversal of current wisdom on pathogen management, where broadly-based hortizontal resistance is considered to be the best means of resolving the long term threat of pathogen evolution. It relies heavily on the accessibility of a reservoir of suitable genes for crop protection.

Genetic erosion

Genetic erosion of crop genetic variability is an inevitable consequence of artificial selection and is as old as crop cultivation itself. The pace of loss of genetic variability has increased rapidly in the second half of the twentieth century, as relatively few highly succcessful, high yielding varieties have rapidly replaced the multiplicity of land races that evolved during the first ten millennia of settled agriculture (Fowler and Mooney, 1990). Some causes and consequences of enhanced genetic erosion brought about by F_1 hybrid technology have been outlined above, but there is a more general threat to the conservation of crop genetic diversity which is posed by the use of crop genetic engineering itself.

In one sense the introduction of genetic engineering techniques drastically widens the pool of genetic variability available to plant breeders, since useful genes from micro-organisms, fungi, and even animals can be incorporated into plants (Steinbiss and Davidson, 1989). Traditional sources of useful genetic variability have been restricted to existing varieties or wild genotypes of crops and closely related, sexually compatible species, which are now maintained in germplasm banks (Ford-Lloyd and Jackson, 1986; Plucknett, *et al.*, 1987; Fowler and Mooney, 1990; Holden, Peacock and Williams, 1993).

Despite determined conservation efforts, the erosion of crop germplasm continues apace (Sattaur, 1989), as a result of habitat destruction and loss of landraces, while the costs of storing germplasm *ex situ* will continue to rise (MacKenzie, 1991). Since all economic enterprises are ultimately subject to cost-benefit analysis there may come a time when the ease of transfer of genes between species, families and even kingdoms will call into question the costs of storing very large samples of germplasm from single species, most of which are unlikely to be used in the short term. The willingness of national and international agencies to continue to fund such enterprises depends on a combination of altruism and vested interest (Stone, 1994) and if the latter is diminished by the availability of genetic variation from other, more diverse sources their financial support may be harder to secure. The net result of such trends could be an increased reliance on molecular biological methods of gene transfer for the future security of most major food crops.

While noting the inherent risks of narrowing the genetic base of widely grown varieties by the use of plant genetic engineering techniques, it is also clear that molecular methods can be used to aid the conservation and utilisation of conventional plant genetic resources in a variety of ways (Ford-Lloyd and Jackson, 1991; Paterson, Tanksley and Sorrells, 1991; Hillman, 1992). These can range from the long-term storage of genetic information in DNA libraries (Peacock, 1989) to the use of RFLP methods to measure genetic diversity within and between accessions of 'wild' and cultivated crops (Flavell, 1989; Crouch *et al.*, 1995) and the use of fluorescent *in situ* hybridisation of DNA probes to identify the chromosomal pedigrees of allopolyploid crops (Young, 1994). Transposon tagging can be used to identify plant genes of agricultural interest (Aarts *et al.*, 1993), while the use of PCR and RAPD technology can help to clarify the pedigrees of varieties and allow breeders to plan crosses which avoid excessive genetic uniformity between varieties (Graham *et al*., 1994). Recently the value of PCR and RAPD technology has been demonstrated as a means to increase the efficiency of management of rice germplasm (Parminder *et al*., 1995). In the longer term, the use of rapid molecular methods for identifying and classifying useful genetic variability in crops, thereby ensuring that germplasm banks are 'functional, representative and predictive' (Hillman, 1992), may prove to be a powerful stimulus for maintaining and extending existing germplasm collections.

High value industrial products and pharmaceuticals

The use of field crops as cost-effective, solar-powered bioreactors for the production of high-value industrial chemicals or pharmaceutical products has become the focus of intensive research (Whitelam, 1995) and is currently the subject of a Biotechnology and Biological Sciences Research Council Wealth Creating Products in Plants Initiative. Plants that will be transformed in this way are likely to contain a broad spectrum of biologically active molecules, including stored proteins, enzymes, lipids, carbohydrates, secondary products, polymers and antibodies which do not naturally occur in current crops and may not be produced by plants in general. Recent advances (Nawrath, Poirer and Sommerville, 1994; Haq *et al*., 1995) suggest that progress in this field will be rapid.

Several hazards can be identified as a result of this application of gene transfer technology. First, and most obvious, is the risk that the products produced may be toxic to wild animals which feed on such crops, either as pests, as benign or beneficial visitors (pollinating insects) or as indirect feeders (predators of pests that feed on crops). Such potential hazards will need to be assessed by toxicity tests on the individual novel products in question, on a case-by-case basis, and by the modelling of the potential for bioaccumulation of these compounds in food chains. Risks derived from feral populations or gene transfer to wild crop relatives can be assessed by the use of techniques already in place, but the nature of the risks involved will depend on the specific gene products. The range of such products involved in this new technology implies that adequate safety testing will require a major commitment of resources to the assessment of direct ecological impacts.

A second hazard arises from the possibility that pollen which carries novel, biologically active products may have allergenic properties that may harm humans. Allergenicity testing is required to assess this potential hazard, which may be minimised by avoiding the use of wind pollinated crops for such purposes and by ensuring tissue specific gene expression (Wilkinson *et al*., 1994).

An additional hazard which may be foreseen may arise when genetically engineered products in plants make them either more attractive to existing pests or to species that are not currently major pests. The expression of fungal phytase genes in tobacco seed (Pen *et al*., 1993) has demonstrated that enzyme from the milled seeds can enhance the release of inorganic phosphate from poultry diets. This example illustrates the potential of genetically engineered, seed derived enzymes for enhancing the performance of domestic animal feeds. It is reasonable to suppose that the incorporation of any genes that enhance the dietary properties of field crop products could have significant implications for pest attacks on the crop or its stored products.

Bioremediation

Genetically engineered plants, equipped with suitable antibodies, have been proposed as cost-effective vehicles for the removal of toxic substances, such as heavy metals and pesticide residues, from contaminated land (Coghlan, 1994). Environmental hazards linked to this application are not specific to genetically engineered species, since untransformed plants have already been used to reduce levels of toxic pollutants such as arsenic, lead, cadmium and mercury in extremely polluted environments (Chigbo, Smith and Shore, 1982). However, if successful application of genetic engineering techniques led to the widespread adoption of this technique various environmental safety criteria would need to be considered carefully.

The first safety criterion concerns hazards due to bioaccumulation of toxins, where the engineered crop may itself become toxic to animals that feed on it or might become a concentrated source of toxins in the food chain. Precedents from past experience with pesticides like DDT (Carson, 1963; Moore, 1987) provide a model for this potential hazard and suggest that limitations may need to be imposed on the use of such crops if a toxic or bioaccumulation hazard is identified.

Secondly, seed production or pollen-mediated gene transfer from bioremediation crops to their wild relatives could lead to the establishment of feral or wild populations of plant species with the potential to accumulate toxins to dangerous levels. The substantial body of data already accumulated in the assessment of herbicide resistant plants in this respect provides some guidance on the magnitude of risks involved, but more accurate analysis would depend on case-by-case studies. The possibility that plants which can sequester harmful pollutants and agrochemical residues may become invasive, because of a competitive advantage over wild-type plants, due to greater resistance to pests or greater tolerance of adverse soil conditions, may also need special consideration.

Environmental tolerance

Tolerance to climatic extremes or to adverse soil conditions holds great promise for increasing crop production. Techniques which enhance salinity or drought tolerance could allow the restoration of agriculture production in saline soils and compensate for some effects of desertification, but these benefits need to be considered alongside potential ecological risks. Specifically, these include the potential to convert naturally saline environments of high conservation value, such as salt marshes, to agricultural production and the risk of generating environmentally tolerant crops with greater potential to become weeds in stressed environments.

Enhanced thermal tolerance of crops promises benefits for agricultural production. For example, improvements in molecular mechanisms of low temperature tolerance in crop plants indicate that it will be possible to extend the geographical range of tropical and sub-tropical crop plants by genetic engineering techniques. There are easily identifiable benefits for countries with pronounced seasonal environments, including lowering of energy costs in glasshouses and reduced threat of frost damage. However, developments which extend the temperature tolerance of non-hardy crops could shift centres of production of tropical and sub-tropical plant products to temperate agricultural ecosystems, thereby undermining elements of the rural economy of developing countries (see below).

Plant genetic engineering in a changing environment

Plant breeders generate new crops on the assumption that their novel, finished varieties will be grown in environments that are broadly similar to those in which they were selected in the early years of the protracted breeding programme. Accumulating evidence of rapid climate change suggests that this assumption may not be valid in the future, and that the expression of important crop characteristics will be affected by global warming (Blumental, Barlow and Wrigley, 1990). The nature and geographical distribution of natural plant communities (Van der Hammen, 1994) and existing agro-climatic zones are expected to shift rapidly (Parry, Porter and Carter, 1990a, b). The effect of climate change on world production is difficult to predict (Daily and Ehrlich, 1990) but techniques designed to meet the challenges of modified pest distribution (Harrington and Woiwood, 1995), shifting disease patterns and the response of crops to altered carbon dioxide levels (Murray, 1995; Culotta, 1995), temperature and rainfall patterns are likely to become major themes for plant biotechnological research (Hillman, 1992). The most conservative estimates of the effects of global warming represent the fastest rates of climate change in the recorded history of crop cultivation. The time scales involved are such that the climatic conditions for cultivating a crop may have changed in the period between the beginning of a conventional breeding programme and the release of a finished variety, especially near the edges of the geographical range of the crop. Plant breeders may find themselves aiming at a moving climatic target (Gates, 1992).

Under these circumstances the use of genetic engineering techniques in plant breeding programmes may become increasingly attractive, since it drastically shortens the period required for breeding crops for a changing environment. This will be particularly valuable in the case of perennial crops and trees, where the conventional breeding cycle is too slow to provide an adequate response to the demands of climate change (Hillman, 1992; Manders, Davey and Power, 1992).

The same set of circumstances will also affect risk analysis. In discussing safety testing of genetically engineered organisms Tiedje*et al.* (1989) noted that 'the absence of an immediate negative effect does not ensure that no effect will ever occur' (*sic*) and this stricture is particularly apposite during periods of rapid global environmental change. Tests for crop-weed gene transfer, persistence of crop propagules after harvest or establishment of feral, weedy populations of crops that are conducted before the authorisation of environmental release of a crop will need to be followed by regular monitoring to assess these parameters under conditions where the climatic constraints on the crop and on the surrounding natural vegetation and fauna will shift.

Costs and benefits

Plant genetic engineering is a triumph of the reductionist approach to biological science, achieving success through the molecular dissection of plant metabolism and the use of this knowledge in the modification of whole organisms. There is a danger that the same reductionist logic will lead to a parochial compartmentalisation of potential environmental problems, concentrating on risk assessment within local ecosystems or within national boundaries, with varying degrees of stringency according to the requirements of national regulatory bodies (Munson, 1994; Plafker, 1994).

This restricted perspective fails to recognise the global environmental significance of the new technology.

Heavy emphasis has been placed on measuring and monitoring the fate of transgenic plants and their genes in local environments in European and North American agricultural ecosystems, but little similar work has been done in tropical and subtropical environments, where there is greater potential for gene transfer between transformed crops and closely-related wild ancestors (Rogers and Parkes, 1995) and for the consequent disruption of natural ecosystems. It is reassuring to know that there is virtually no likelihood of gene transfer between genetically engineered cultivated potatoes and the few, distantly related *Solanum* species that occur as weeds in agricultural ecosystems in Europe or North America (Tynan, Williams and Corner, 1990; Eijlander and Stiekema, 1994; Love, 1994), but the more important question concerns the impact of gene escape from transformed potatoes to wild ancestors in South America. Gene flow from transformed crops needs to be measured in their centres of diversity, and not just on the edge of their range, especially if the avowed objective is to transfer the benefits of the technology to needy Third World countries where the transformed crops are indigenous and are grown beside wild progenitors (Kareiva and Parker, 1994).

Environmental risk assessment has focussed most closely on the escape of transformed plants and their genes into agricultural ecosystems. Although many of the data obtained so far can be criticised on the basis that results from small plots cannot be extrapolated to the effects of mass releases of commercial crops (Regal, 1994), the available evidence suggests that although gene transfer from transformed crops to wild species is likely this will not be considered to be sufficiently hazardous on a local scale to prohibit the release of many genetically engineered crops in advanced Western agricultural ecosystems (Rogers and Parkes, 1995). In the global context the economically-mediated impact of the adoption of these varieties on developing countries may have far greater environmental significance.

Past experience of the transfer of technological innovation to developing countries during the 'Green Revolution' has shown that the benefits accrued from increased overall crop production must be set against environmental damage, largely brought about by rural demographic and social changes that are precipitated by rapid alterations in farming practice and profitability (Smith, 1990). Technological innovation favours well capitalised farmers who own large farms and can secure bank loans to pay for the superior crop varieties and the support materials needed to grow them, while the resulting increase in production efficiency can drive down prices and force small farmers out of business (Buckwell and Moxey, 1990).

The adverse social and economic changes in Third World countries brought about by the 'Green Revolution' largely resulted from such changes in production efficiency and production levels. Plant genetic engineering has the potential to bring a further intensification of the long-standing problems of technology driven socio-economic change in the Third World. It could, for example, allow the developed world to dispense with the import of certain third world plant products altogether (Häyry, 1994). Genetic manipulation of lipid composition of temperate oilseed crops, so that they can substitute for imports of palm oil from South East Asia, may represent no threat to natural ecosystems or wild native species in temperate countries but may undermine the economies of countries that are traditional sources of supply (Kleiner, 1995; Stumf, 1995). Similar consequences may flow from an eventual switch of pyrethroid supply from traditional Kenyan farmers to cell fermentation systems in North American laboratories.

Past experience shows that such circumstances often lead to an undesirable dislocation of Third World rural communities, with a drift of populations into overcrowded cities, deterioration of rural communities, loss of export revenue leading to international debt, decline in investment in infrastructure and social services and even political instability (Busch *et al.*, 1991). These are all consequences with profound and widespread environmental implications in developing countries. There are many historical precedents for the major disruption of economies caused by switches in production centres and production methods of plant products, including the impact of sugar beet production on the sugar cane industry in the West Indies and Far East, the decline of the indigo industry in Bihar Province in India after the development of synthetic dye substitutes and the switch in rubber production from Brazil to Malaya.

The ability of a small cadre of innovative researchers in laboratories in technologically advanced countries to devise means of manipulating or substituting the supply of plant-derived industrial and food commodities, with adverse economic effects on Third World nations that are foreseeable in the light of past experience, begs major questions concerning the motives, social responsibilities, conflicts of interest and accountability of the agricultural scientific research community (Crouch, 1990; Medford and Flores, 1990; Busch *et al.*, 1991).

Almost all scientific reviews and many primary research papers stress the environmental benefits of plant genetic engineering in tackling environmental problems, conserving renewable resources and feeding a world population which is projected to more than double during the next century (Bongaarts, 1994). While there is good reason for optimism that plant genetic engineering may make an important and durable contribution to some of the resulting problems, the early products of the new technology have generally been high value consumer products whose commercial benefits are largely confined to the developed world (Schmidt, 1995). This trend has been driven by the potential of biotechnology for wealth creation in the developed world (Blundell, 1993) and the high development costs of the new technology (Miflin, 1992), which must be paid for by the commercial success of its products before its benefits can trickle down to the Third World economies where the greatest need for genetic engineering's potential benefits exists (Tudge, 1993).

Although enthusiasts for plant genetic engineering are often at pains to stress to the public that it is little short of a 'revolution' in our ability to exploit plants and their products (Gasser and Fraley, 1992), the foreseeable global environmental impacts of the new technology are likely to be little different from those of conventional international agriculture. The major distinction between old and new technologies lies in the speed and precison of plant genetic engineering techniques, which are likely to increase the pace of economically-driven environmental change that has been fuelled by innovations in agriculture throughout history. The pattern of change progresses through a transition from small scale peasant agriculture, through consolidation into larger, more efficient farms with lower labour inputs, higher energy and technology inputs and higher plant product outputs. This is accompanied by growth in rural unemployment, expansion of urban populations, industrialisation, consumer industries and intensification of fossil energy use, which in turn are the source of many of the most pressing global environmental problems. The environmental challenge for plant genetic engineers is to recognise the impact that their inventions will have on these processes and to identify applications of the technology which will minimise the worst environmental consequences of agricultural and industrial development. In many cases beneficial innovations will come from laboratories within the Third World (Mabbett, 1991a,b; Moffat, 1994), where familiarity with the real problems should lead to the most appropriate solutions. In comparison with these macro-environmental effects, the risks of the spread of herbicide resistance genes into wild *Brassica* species from oil seed rape in the developed world are only of relatively minor, short term significance.

Some conclusions

In applications for funding, research papers and reviews, plant genetic engineering practitioners almost invariably describe technological innovations and highlight potential benefits with varying degrees of hubris, but often minimise or ignore possible environmental risks. Claims made for the environmental benefits of innovations, such as the development of herbicide-resistant crops, are rarely supported by any attempt at a detailed cost-benefit analysis that takes account of all potential environmental impacts (Gates, 1995). Closer links between universities and the biotechnology industry have clearly made scientists more aware of the commercial benefits of their work, but a similar multidisciplinary approach linking technological innovation with its broader environmental and socio-economic impact has yet to permeate the culture of science laboratories.

The agenda for discussion and investigation of the broader environmental consequences of the new technology, of the kinds outlined above, is left largely in the hands of non-governmental organisations with a more general (but nonetheless often expert) appreciation of the wider ramifications of its introduction (Anon, 1994a, 1995; Goodwin, Ho and Regal, 1994; Kareiva and Parker, 1994; Meister and Mayer, 1994; Miflin, 1992; Nuttall, 1994). There is clearly public concern about the risks of genetic engineering in crops, not only in terms of their safety in developed countries but also in terms of the fair and equitable impact of their use on the developing world (Anon, 1994a).

By default, an adversarial situation has developed in biotechnology, where the practitioners of plant genetic engineering research are generally perceived as enthusiastic proponents for its rapid practical application, while non-governmental organisations and pressure groups which espouse the precautionary principle occupy the moral high ground and campaign for more equitable use of the new technology and more stringent safety measures. Such a situation promotes conflict and conveys an impression that research is being conducted and presented without the objectivity and balanced scepticism which is generally considered to be the prime characteristic of scientific investigation.

This unhealthy situation might be redressed to some extent if it became the norm for the scientific reporting of plant genetic engineering innovations to carry a short but clear environmental impact assessment, listing foreseeable benefits *and* risks of their commercial implementation and identifying information gaps and uncertainties that may have environmental consequences (Lindsay, 1995). The implementation of such an innovation could become part of the normal refereeing process of scientific publications and would promote public confidence that science's practitioners were aware of the wider implications of their research. It would also require the participation in basic research programmes of personnel with a much wider range of expertise, moving towards fulfilment of one of the major recommendations of the Ecological Society of America's policy statement on the planned introduction of genetically engineered organisms (Tiedje *et al.*, 1989), which advised that 'for society to realize the full benefits of biotechnology, interdisciplinary research and graduate training programmes are needed to expand the expertise of the scientific community at large'. It would seem that the time is ripe to strengthen links between disparate disciplines in applied plant science, links that have become increasingly isolated and polarised over four decades of specialisation, in order to develop the new science with a fuller appreciation of its environmental, social and economic implications.

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