Managing the Ecological Impacts of Genetically-modified Agricultural Crops: Changing Patterns of Agrochemical Use, On-target Effects and Gene Flow

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ABSTRACT

GM crops are now grown extensively around the world. Nevertheless, their use is contentious, reflecting concerns over food safety, health and environmental effects. The initial GM traits to be commercialised were for pest resistance and for herbicide tolerance. GMHT crops are widely grown, but attract concerns in regard to the movement of the trait to the same and related species, gene stacking and the impacts of broad spectrum herbicides on weed assemblages. Introduction of GMHT crops impacts on herbicide use, potentially increasing the efficiency of weed control, the likelihood of drift to non-target areas and of trophic effects. The use of buffer strips at field edges and areas set aside for farmland biodiversity may be one means of mitigating such effects. Whilst biodiversity concerns are not the same across the globe, where agriculture has evolved its own associated fauna and flora, GMHT crops provide another means of intensification. Gene flow seems to be inevitable for many traits. Therefore the key questions must address the acceptability of the impact of that gene following movement and impacts within the agroecosystem. The challenge is to develop relevant farming systems for different environments, different climates and different societies. Each requires an appreciation of the multi-functionality of the farmed environment. GM technology should be able to contribute to those systems, so long as it is used wisely and is not regarded as the single answer to all agricultural advances.

Key words: *GMHT crops, non-target effects, biodiversity, field margins, weeds*

1. INTRODUCTION

Genetically-modified (GM) crops offer a range of potential benefits to farmers, growers, and ultimately to consumers. Genetic modifications to crops can range from incorporating pest and disease resistance genes, herbicide tolerance genes, to genes that engineer the production of specialist oils, pharmaceuticals and other products. In addition, there is considerable interest in developing crops that are capable of withstanding environmental limits to growth. For example, salt tolerance, frost tolerance and nitrogen fixation are all targets of genetic engineering to enhance crop performance. In addition, there is considerable interest in the food industry in more cosmetic changes to crops, e.g. fruit colour, as well as perhaps more altruistic modifications, such as enhancing levels of vitamins (Dunwell, 1998).

Whilst not many of these benefits have been realised, there have been a number of modified crops released for field use in different countries round the globe. GM crops are grown extensively in the USA, Canada, Australia and China. In Europe, there has been a moratorium on the general release of GM crops, reflecting the high levels of environmental and health awareness amongst the general public. The growth of GM crops remains a highly contentious issue in Europe, reflecting worries over commercial globalisation, environmental risks, food safety and perhaps more philosophical issues. The private ownership of genetic information is regarded by some as unethical. The profit motive is seen by such people as incompatible with the exploitation of genetic information. Aspects of the ungoverned exploitation of genetic capital were addressed at the Rio Summit that resulted in the International Convention on Biodiversity in 1992. Specifically, discoveries in individual countries made by foreign companies could not be exploited without the agreement of those countries. Nevertheless, the Convention indirectly promoted the commercial ownership of genetic information. This has resulted in the development of commercial GM crops and the expenditure of large amounts of money on research and development.

The commercial growth of GM crops has increased markedly over recent years. More than 50 million ha of GM crops were grown in 2001 (Fig. 1). GM crops are grown in a number of countries (Table 1), with the majority in the USA.

Whilst the first generation of GM crops have provided production and environmental benefits, they have provided little direct benefit to consumers (Robinson et al., 2000). Second generation GM crops are likely to provide more direct benefits to food processors and consumers. It is generally accepted that the GM technologies have associated risks and some commentators have been critical of the overall approach, e.g. (Steinbrecher, 1996). However, the standard of debate has poor and others have attempted to introduce more reasoned argument (Pretty, 2001; Tester, 2001). Pretty (2001) notes seven types of risk that apply to agricultural systems in regard to GM crops (Table 2).

The new European Union (EU) Directive on the release and commercialization of genetically modified (GM) crops (2001-18-EC) includes a requirement for an assessment of indirect effects on the environment of farming practices associated with the introduction of a GM crop. There is also a requirement for post-commercialization monitoring to address impacts of scale and time.

The first GM crops that had been released for commercial use contained a range of genes. These were crops containing Bt genes for pest resistance, notably cotton, glyphosate and glufosinate resistant crops to improve weed control and modifications in tomatoes for delayed ripening and frost resistance. Genetically-modified herbicide-tolerant (GMHT) soybeans, cereals and oilseed rape (canola) were the first major crops to be modified and used on a large scale. As such crops have been grown commercially for some time, this paper will focus on their impacts, so far as is known, but will also examine the many attempts to model the impacts and spread of transgenes, notably in Europe. GMHT soybeans have proved to be extremely popular in the USA, providing good weed control and facilitating crop management (Reddy, 2001). Nevertheless, continuous GMHT cropping may bring problems with it, in terms of weed community shifts and increasing resistance. Conventional weed management, using tillage, crop rotations and herbicides, have affected weed communities. Recently, it has been suggested that weeds within crops are important to other trophic levels within agricultural ecosystems (Marshall et al., 2003). The effects of direct weed removal and indirect impacts of herbicide drift may adversely affect plants and their associated insect, mammal and bird assemblages.

This paper will concentrate on GMHT crops, reflecting the importance of these crops in commercial agriculture, but will briefly consider other traits. The objectives of this paper are 1) to examine the impacts of the introduction of GM crops, 2) to examine the likely patterns of non-target effects associated with GMHT crops, 3) to review the available information on gene flow and transgene movement, in order to 4) propose the best means of managing GMHT crops and 5) to comment on the likely impacts and management of other GM traits that are being introduced into crops.

2. THE IMPACTS OF INTRODUCED GM CROPS

The likely adverse impacts of GM crops have been reviewed by others, who note that gene flow may be the main risk, associated with both within and between species movement (Kwon & Kim, 2001). Nevertheless, where crops have been introduced, there are have been undoubted benefits to crop management, though there are also a few problems that have been identified (Lutman & Berry, 2003). In general, there is little published scientific data on the field experience of growing GM crops, but a selection of reports are reviewed below.

The introduction of GMHT canola in the USA and Canada was welcomed by farmers, as it facilitated crop management, simplifying weed control operations. One result was an increase in the use of the appropriate herbicides. For example, *Agrow* No. 307 (p.14) 26 June 1998 reported a 72% increase in the use of glyphosate in the USA, coincident with the introduction of Roundup Ready soybeans. In glufosinate-resistant maize, studies indicate that the effects of weed competition early in the life of the crop are such that pre-emergent herbicide application as part of a spray programme still gives the best yield and economic return (Bradley et al., 2000). Thus, in some modified crops reduced herbicide programmes may not necessarily result from their introduction. Nevertheless, the economic indications are that for some crops in Europe, the introduction of GM technology would enhance profitability, for example sugar beet (May, 2003). A recent review of beet production in Germany noted that the continuing production increases have relied on crop breeding, with inputs, particularly fertilisers, declining. There is particular potential for GM crops to contribute to the industry (Marlander et al., 2003).

GM pest resistant cotton was released for commercial production in 1996 and has been shown to have important economic and environmental advantages (Perlak et al., 2001). Cultivars incorporating Bt genes are now grown on one third of the USA's cotton area, demonstrating a safe and successful approach.

More than half of the world acreage of GM crops is sown with modified soybeans (Reddy, 2001). This has been facilitated by farmers using a single more effective herbicide that is cheaper than the range of alternatives for unmodified cultivars. However, the use of a single herbicide creates a high selection pressure that may encourage the evolution of resistance and may modify weed assemblages (Reddy, 2001).

Buckelew et al. (2000) have shown that herbicide-resistant soybean crops tend to have lower insect population densities than similar conventional cultivars. The effect is mediated through the impact of weed management, rather than direct effects of herbicide. Cleaner crops support fewer insects. Whilst the indirect effects of weed removal may impact on insects within crops, a study on two GMHT and two conventional oilseed rape cultivars showed no differences in insect pollinator numbers or behaviour associated with crop flowers (Pierre et al., 2003). Nevertheless, the authors suggested that a case-by-case approach to testing such effects might be required.

There has been one development with the commercial growing of oilseed rape that has provided reports of some negative effects of the GMHT approach. In Canada, oilseed rape volunteers have been found to contain three different GM herbicide tolerance genes (Orson, 2001). This example of gene stacking demonstrates that gene flow occurs. It is also of concern that potential weeds are developing resistance to a range of herbicides, adding to the popular myth of the creation of "super weeds".

Concerns in regard to food safety have been a major factor affecting the acceptance of GM crops and products. These concerns are not static and change over time. For example, there may have been a change in the public attitude against GM food in Japan (Nishiura et al., 2002). Some of these concerns are unlikely to be based on scientific fact. Nevertheless, the possibility of introducing allergens into products is a legitimate concern that should be built into testing regulations (Kuiper et al., 2001). It is also generally accepted that food products should be labelled accurately in regard to GM content. Nevertheless, there is debate on tolerance levels of GM material and methods of assessing that material. Some food sectors, notably the organic (biological) food producers, are demanding zero levels of GM in their products. This may prove difficult to achieve and may require agreed minimum levels (Dale, 2002). In practice, field kits to determine levels of herbicide tolerance in soybean samples have been shown to be unreliable at low levels of contamination (Fagan et al., 2001).

Despite the enormous acreage of GM crops grown around the globe, it is an important concern to environmentalists that there has been little ecological investigation of the impacts of such crops. The work that has been published indicates that there are few if any direct impacts, but indirect impacts may be important (see on). Nevertheless, it is clear that following the introduction of GMHT crops, patterns of herbicide use change. With many pest resistance GM crops, the use of pesticides is significantly reduced, with potential benefits to non-target fauna. The ecological impacts of four GMHT crops have been the focus of large-scale field experimentation in the UK (Firbank et al., 2003). The results of this field study, which has employed split fields of GM and non-GM cultivars, will be released in late summer 2003.

3. INDIRECT AND NON-TARGET EFFECTS ASSOCIATED WITH GMHT CROPS

The introduction of GM technology is unlikely to have direct adverse effects on products or the environment, though this remains a possibility via the production of toxins, e.g. Bt proteins, allergens. There is a small possibility that genetic material from GM plants may become incorporated into soil bacteria and move between species. However, indirect effects, mediated by changes in crop management and gene flow, may be much more important. The objective of GM pest and disease resistance is the prevention of crop damage. Where this may be achieved by direct toxicity to pests, diseases or disease vectors, there is some risk of the proteins coded by the gene, affecting non-target species. This may be overcome by specificity of action or by limiting exposure. In the case of GMHT crops, the risks are associated with changes in crop management, the crops themselves becoming weeds and the movement of the gene to target weeds.

First, it may be useful to review the approaches to crop management, farm support and the integration of biodiversity concerns into agriculture in different countries. In the heavily populated north western Europe, 50 % of the land surface is in agriculture. In the UK over 95% of the land is managed, mostly as farmland. Under such conditions, land has many functions; as well as providing food, it is used for recreation, nature conservation, biodiversity, water catchment and has historical value and heritage. In many countries, biodiversity and nature conservation are catered for in wilderness areas and are of no concern in agricultural production areas. Under such conditions, the environmental concerns expressed over GM technology seem of little consequence. However, in Europe and increasingly elsewhere, there are attempts to conserve biodiversity in agroecosystems and there are supporting mechanisms for farmers to achieve this. Financial payments can be made to farmers under agri-environments schemes (Hart & Wilson, 1998; Kleijn & Sutherland, In press; Tahvanainen et al., 2002). This in part is based on the exploitation of functions provided by biodiversity, such as nutrient cycling and natural pest control. In addition, there is a realisation that agroecosystems have evolved over the millennia alongside man and have developed their own assemblages of fauna and flora, some of which are threatened by the rapid advances in agricultural technologies of the past 50 years. In the UK and elsewhere in Europe, it has become apparent that some species commonly found in farmland have shown highly significant declines in population size and geographical range over the past 30 years. For example, many common birds have declined in the UK (Fuller et al., 1995), some by over 90% (Table 3).

Agricultural intensification, in both arable and grassland areas of the UK, has been shown to play an important part in those declines (Baillie et al., 2001; Chamberlain & Fuller, 2000; Chamberlain et al., 2000; Siriwardena et al., 2000, 2001). Potential mechanisms are reviewed by (Fuller, 2000), and include pesticides, though only for one species, the grey partridge, has a relationship between pesticide use and population decline been conclusively demonstrated (Burn, 2000; Campbell et al., 1997).

Amongst the plant species found in agricultural land there are many annual weed species. A proportion of these have evolved with arable cropping, but have not been able to adapt well to changes in mechanisation, crop husbandry and weed control (Wilson, 1990, 1993). Some of these species are now the subject of conservation concern in the UK, such as broad-leaved cudweed (*Filago pyramidata*), and some are included within UK Biodiversity Action Plans (BAPs), the UK response to the Rio Convention on Biological Diversity (Anon, 1994). Whilst such species, by their nature, are unlikely to be of major significance to populations of other common taxa, changes in habitats and food resources provided by common weeds are implicated in some population declines. Weeds may be important in providing food and cover for many insect and bird species (Marshall et al., 2003; Marshall et al., 2001).

Models of introducing GMHT oilseed rape crops in the UK have indicated potentially important effects on seed-eating birds (Watkinson et al., 2000). If superior weed control is achieved, weed seed availability may decline to levels that affect farmland birds. Thus the management of the crop, rather than the genetic modification *per se*, may affect biodiversity.

(Buckelew et al., 2000) have shown that herbicide-resistant soybean crops tend to have lower insect population densities. The effect is mediated through the impact of weed management, rather than direct effects of herbicide. Where weeds are controlled with herbicides, insect densities may be reduced, e.g. (Moreby & Southway, 1999).

If GMHT crops result in similar or higher levels of weed control than at present, then it is likely that some plant and animal species dependent on farmland may continue to decline.

Herbicide drift

Non-target drift of herbicides from conventional application machinery occurs over relatively short distances of 1 to 10m. In some parts of Europe, the linear landscape features that form field boundaries between fields are important habitat for plants and animals (Marshall, 2002; Marshall & Moonen, 2002). Data from large-scale surveys show these elements, notably hedgerows, verges and riparian areas, are refugia for many plant species (Barr et al., 1993). However, many of these elements are subject to disturbance from agricultural operations that can result in species-poor plant assemblages. One of these disturbances is provided by pesticide drift. Significant amounts of drift can occur into field boundaries (Breeze et al., 1999; de Snoo & de Wit, 1998; Longley et al., 1997; Longley & Sotherton, 1997a, b). Studies of the effect of herbicide drift on native flora indicate that effects may occur (de Snoo & de Wit, 1998; Kleijn & Snoeijing, 1997; Marrs et al., 1993). The herbicides that appear to have the most effect on non-target species include broad spectrum compounds, notably glyphosate (Marrs et al., 1993; Marshall, 1987). The development of GMHT crops based on resistance to broad spectrum herbicides can be regarded as unfortunate, from the viewpoint of possible drift effects into field boundaries. Widespread and increased use of glyphosate would increase the risk of drift and damage to adjacent plant communities. The experience from the USA following the introduction of glyphosate-resistant soybean was that glyphosate use increased markedly (by over 70% in 1998). This might be of particular significance, as the herbicide would be used at a time of year (spring and early summer), when it has not been widely used before and when it could be argued that many plants are in full leaf. Most glyphosate use in arable crops is currently pre-harvest or associated with pre-cultivation weed control, notably in autumn.

There are possible means of mitigating such drift effects, particularly the creation of buffer strips of perennial vegetation at the field edge (Marshall & Moonen, 1998) (Fig.2). Studies in the UK with and without grass strips have shown that botanical diversity is enhanced where such strips are grown (Moonen & Marshall, 2001). In addition, certain annual weeds associated with the field boundary are less prevalent where grass strips are present, demonstrating an element of weed management. A requirement for such strips, where GMHT crops are grown, would reduce drift of broad spectrum herbicides to non-target areas and help satisfy biodiversity requirements.

Increased selection pressures

It is well known that the effect of applying herbicides continuously can encourage the development of resistance (Caseley et al., 1991). Herbicide resistance has developed in many weed species and in many countries. Initially repeated use of triazine herbicides was found to encourage resistance. Now, evolved resistance is known for hormone herbicides, sulfonyl ureas and phenoxy and oxime graminicides. The evolution of resistance reflects the selection pressure applied within the crop (Richter et al., 2002b). In GMHT crops, as in other crops, herbicide use provides a selection pressure. The concern is that the same herbicide programme will be applied each time the cultivar is grown, so repeated selection events will occur and the speed of development of herbicide resistance will increase. This may compromise the longer term sustainability of the technique.

Super weeds and volunteers

A related concern over the introduction of GMHT crops is the movement of the resistance genes to related species and the creation of so-called "super weeds" which are difficult to control. Another concern has been GM crop volunteers as resistant weeds. Many crops are weeds in following crops (volunteers), so if these are resistant to herbicides, they will be harder to manage. This concern has increased with the reports of gene stacking in oilseed rape (Orson, 2001). In Canada, oilseed rape volunteers have been found with up to three herbicide resistance genes. This could increase the rate of evolution of multiple resistances in weeds (Kwon & Kim, 2001), as well as adding to the difficult of control.

4. GENE MOVEMENT

The means by which transgenes may move from a sown crop include the simple physical movement of seeds after harvest, spatial and temporal dispersal of seeds that form crop volunteers, and active and passive pollen flow with subsequent hybridisation. Pollen movement can be by simple wind dispersal, or by pollinating insects, depending on the plants under consideration and their breeding system. Outcrossing species are more likely to form hybrids in comparison with inbreeding species.

For some crops, weedy volunteers in following crops may become a problem, for example oilseed rape. Reciprocal gene exchange between cultivated sugar beet and wild beets in seed production areas is probably the reason for the occurrence of weed beets in sugar beet production fields. In beet crops, those plants that carry the bolting gene might also gain transgenes, e.g. for herbicide tolerance, if care is not taken in the methods used in those seed-producing areas (Desplanque et al., 2002).

Gene flow is a reality in the plant kingdom. Herbicide resistance evolves naturally and spreads dynamically in weeds (Kwon & Kim, 2001). The potential for gene flow is greatest in outcrossing crops, such as oilseed rape. It is lower in inbreeding crops, such as cereals and rice. Nevertheless, it will occur in rice (Song et al., 2002). Hybridisation between native and bred cultivars of soybean has been demonstrated the possibility of gene flow from this crop (Nakayama & Yamaguchi, 2002).

A concern has been that transgenes in crops might spontaneously move as hybrids formed with closely related species. This possibility has been demonstrated in France, between *Brassica napus* L. (oilseed rape) and *Hirschfeldia incana* (L.) Lagrèze-Fossat (Lefol et al., 1995). It has also been shown between oilseed rape and *Raphanus raphanistrum* (wild radish), with the frequency of hybrids expected to range from 0.006 to 0.2% of the total seed produced (Darmency et al., 1998). Further studies have examined the fitness of the parents and the F1 progeny (Gueritaine et al., 2003). The hybrids have lower fitness in terms of emergence and survival, indicating that the risks of transgene escape are not great. Similar studies weedy *Brassica rapa* also indicate that introgression will be slow, but still possible (Hauser et al., 1998). The average rate of spontaneous hybridization between *Hirschfeldia incana* and oilseed rape was 0.6 hybrids per plant over 3 years of field experiments using herbicide-resistant oilseed rape as a pollen donor (Darmency & Fleury, 2000). However, successful introgression was not found in the species. Whilst hybrids with *Sinapis arvensis* L. can form, a recent field study with a number of rape cultivars found no hybridisation, confirming the low probabilities of successful gene flow (Moyes et al., 2002).

Pollen movement via insects, in particular bumble bees, has been investigated using oilseed rape and a modelling approach in the UK (Cresswell et al., 2002). The model predicted that bees accounted for a maximum of progeny of between 0.1 and 0.5% in the fields examined. However, because of bee behaviour, these were likely to be overestimates (Cresswell et al., 2002). Molecular techniques may aid the tracking of pollen movement and gene flow (Hudson et al., 2001).

Pollen movement from grasses have been studied in some detail for certain species. For example, a study of *Festuca pratensis* has shown rapid decline in wind dispersed pollen measured as gene flow over 75 m, and there were significant effects of pollen competition (Rognli et al., 2000). Nevertheless, pollen can travel passively for 1000 m and tests with bait plants of beet have shown transgenes can move significant distances in pollen (Saeglitz et al., 2000). Under such conditions, planting a strip of a tall buffer plant (hemp) was of little value, as transgenic plants were found up to 200 m beyond the strip (Saeglitz et al., 2000). A study of hybrid creation using *Lotus* species indicated limited movement from small plots (18m), but pollen movement to 120 m from a larger plot (14 m^2) (Marchis et al., 2003).

Whilst pollen is likely to move long distances (several hundred m), it has been shown that recipient plants that also produce pollen will dilute donor pollen. This effect is known as pollen competition and will significantly reduce successful hybridisation in outcrossing species.

Gene flow and introgression from cultivated plants may have important consequences for the conservation of wild plant populations. Cultivated beets (sugar beet, red beet and Swiss chard: *Beta vulgaris* ssp. *vulgaris*) are of particular concern because they are cross-compatible with the wild taxon, sea beet (*Beta vulgaris* ssp. *maritima*). However, studies where the species grow in close proximity support the contention that gene flow from the crop to the wild species can be substantial (Bartsch et al., 1999). Interestingly, the introgressed populations had higher genetic diversity than those that are isolated from the crop. The crop-to-wild gene flow rates are unknown, as are the fitness consequences of the studied alleles in the wild. However, it is clear that gene flow from a crop to a wild taxon does not necessarily result in a decrease in the genetic diversity of the native plant.

Modelling has become a popular method of examining the likely movement of transgenes. Recent papers have utilised a spatial approach, using cellular automata (Richter et al., 2002a) or other means (Thompson et al., 2003) to assess gene flow. Spatial and temporal spread of resistance can by reduced by a number of different management approaches, including ceasing to grow the crop, by modifying herbicide programmes, reducing doses and by introducing fallow strips between fields. Generalised models can also inform the process of field trialling GM crops and necessary separation distances (Thompson et al., 2003).

In complex agricultural landscapes, approaches to understanding the dynamics of oilseed rape volunteers have resulted in the development of models (Colbach et al., 2001a, b). The GENESYS model incorporates population dynamics of seed banks, crop rotation and cultivations. Deterministic models that cover a small region and also the evolution of genotypes, notably for herbicide tolerance, indicate that over a period of up to eight years, transgene escape might be significant. The inclusion in the model of field borders and roadsides, where management of volunteers may be different to the field centre, could contribute to transgene movement (Colbach et al., 2001b). Whilst the model includes a number of assumptions that simplify reality and which may not accurately simulate all movements, significant transgene movement is likely.

The output from a number of studies, including modelling exercises, have informed the debate on separation distances between GM and non-GM cultivars to prevent introgression. In practice, the long distance movement of pollen is such that even low probabilities of gene flow will still allow some movement of genes. Inevitably, therefore, there is likely to be some gene flow between some crops, if GM cultivars become widely planted. Inbreeding species, such as maize, can have relatively small separation distances, while crops such as oilseed rape will require larger distances. In the UK the field scale evaluations of GMHT cultivars have used separation distances advised by the industry (Table 4).

In the UK and elsewhere, organic cropping is a minor part of the agricultural industry. There is a requirement in the UK that there be no genetic contamination of organic crops or products. Discussion on separation distances between GM and organic crops has been vigorous and recommendations have been made for different crop types. Nevertheless, the proportions of GM to organic crops may impact on the practicality of imposing particular separation distances (Perry, 2002).

To reduce gene flow of GM crops, it has been suggested that at the development stage, this aspect should be built into the genome. This might be by preventing pollen formation (male sterility) or by ensuring that seeds do not fall from the crop (Kwon et al., 2001).

5. MANAGING GMHT CROPS

While the public debate on GM crops initially focussed on the likely effects on food, environmental impacts have become more of the focus of concerns. Most regulatory authorities have rigorous approaches to food safety, and concerns in regard to GM crops and crop products are mostly covered by extensive testing. In the UK, one of the reasons that the debate has been particularly intense is that virtually all changes in agricultural practice have an adverse impact on wildlife, particularly when such change leads to increased intensification (Beringer, 2000). The problem of deciding how to manage agriculture to ensure that we maintain or enhance species diversity of wild plants and animals needs to be discussed against the background that most of the UK (and northern Europe) environment is the result of human intervention. This may or may not be the case in other parts of the world. In Canada, for example, there are extensive areas of wilderness. In the agricultural areas of Canada, not only have modern agricultural crops been introduced into a new environment, but the associated weeds are almost all non-native as well (Pers. comm. Gordon Thomas, Agriculture Canada). Thus the ideas of farmland biodiversity put forward from Europe may not resonate elsewhere in the world. Nevertheless, the principle that biodiversity promotes ecosystem functions is beginning to be investigated more widely (Paoletti et al., 1992).

Agricultural GMOs pose a range of potential environmental and health risks (Table 2) (Pretty, 2001). A number of approaches are being developed to address the seven risk areas identified by (Pretty, 2001). Gene flow via pollen movement might be prevented at source, by limiting pollen production. This seems rather drastic and might have unwanted impacts on pollinating insects, though pollen incompatibility and changing flowering times might offer more ecological methods. Separation distances and buffer crops will perhaps reduce pollen movement and gene flow, but the evidence is that it will not prevent it completely. Gene flow is inevitable. The basic question must therefore be: *does it matter if this gene moves?* Logically, if the answer is yes, then the trait should not be used for transformations in crops.

Risks associated with new forms of resistance, recombination and effects of novel toxins and allergens produced by GMOs, should be assessed as part of regulatory approval schemes for modified crops, using laboratory and proscribed microcosm and field evaluations. There are alternatives to using antibiotic marker genes that the industry is using more widely. The final risk, that of biodiversity loss, is perhaps more problematic.

In Europe and elsewhere, regulatory authorities are putting in place mechanisms to evaluate and licence the release of GM crops. In Europe, the new EU Directive on the release and commercialisation of genetically modified crops (2001-18-EC) sets out the requirements, including the socio-economic impacts that may result from new crop introductions (Dale, 2002). Whilst some regard these initiatives as a threat to progress, and even to traditional crop breeding (Conner et al., 2003), others regard these requirements as essential to safeguard biodiversity.

Whilst some environmentalists continue to criticise the technology, others regard this as an opportunity to advance more sustainable productions systems. Preliminary studies of aphid populations on beet plants (Dewar et al., 2000) that were resistant to the herbicide glyphosate, indicated that early-sprayed plots had higher pest aphid populations than weedy or late-sprayed plots. The weedier plots supported large numbers of a different aphid species, accompanied by predators and parasites that eventually caused substantial aphid mortality. A novel system of weed control in GMHT sugar beet has now been developed, that shows potential for maintaining reasonable weed cover and associated insects that may benefit birds (Dewar et al., 2003; Pidgeon et al., 2001). The crop is grown in rows and the technique exploits band spraying, as well as leaving weeds for longer in the crop.

The ecological impacts of three spring-sown GMHT crops (oilseed rape, beet and maize) and winter GMHT oilseed rape have been the subject of a large-scale study in the UK (Firbank et al., 2003). The approach has been to examine the fauna and flora of split fields, half sown with a conventional cultivar and half with a GMHT cultivar. In practice the approach has been to compare the overall impacts of the different management packages, specifically the herbicide regimes, applied to the two halves of each field. Large numbers of fields have been used, in order to provide sufficient statistical power to detect differences (Perry et al., 2003). While the results have yet to be released, a number of questions in regard to the design of the study have been posed. In particular, is a single year of growing a GMHT crop sufficient to give insights into effects on flora and fauna that may show variable population cycles from year to year?

The two areas of threat to biodiversity can be regarded as those within the crop area and those that are off-target and to adjacent habitats. Considering GMHT crops only, the threats to biodiversity within the crop are essentially the same as for conventional crops. Elimination of non-crop flora has indirect effects on higher taxa. The possibility that GMHT crops will allow even greater efficiency of weed control is a particular concern to those whose primary interest is biodiversity conservation. Whilst there may be opportunities to modify practices with the technology, e.g. in sugar beet (Dewar et al., 2003), experience of farmer practice would indicate that the most time and cost efficient methods will be used. For example, it is well known that maize is particularly susceptible to weed competition early in its growth. GMHT maize (as are conventional cultivars) will therefore be sprayed early and the idea of leaving weeds to later in the growth cycle will not be welcomed by farmers. Where biodiversity is important, GMHT crops seem to offer little advantages over conventional crops.

In considering off-field effects of GMHT crops, the threat of drift from broad spectrum herbicides to adjacent habitat can be simply addressed by introducing buffer strips (Marshall, In press). There is good data to demonstrate that by moving application machinery 6 m from field boundaries, spray deposition is dramatically reduced (de Snoo & de Wit, 1998) (Fig. 3). Buffers might be created by the introduction of 6 m vegetation strips, which may have agronomic and biodiversity benefits of their own, or by no-spray strips.

It seems strange that the approaches to pest and disease control using GM technology have concentrated on adding resistance to crops, but the opposite approach has been taken with weed control, by including herbicide resistance genes (Marshall, 2001). GMHT approaches may have a place in some systems, but in general it would be more valuable to breed weed resistance into crops. For example, some crops have some allelopathic potential against weeds. Oats have been shown to adversely affect weeds in the UK (Wilson et al., 1999) and the approach is suggested by others (Kim, 2001). The use of herbicides has provided flexibility to farmers during the last 50 years, a period of expanding herbicide development. However, resistance problems, changes in weed communities and the relatively small number of new active ingredients developed nowadays, mean that herbicides alone are no longer sufficient for weed management (Kudsk & Streibig, 2003).

6. LESSONS FOR OTHER GM TRAITS

The main point that this review illustrates is that the particular trait that is under consideration is the key factor to consider. It seems inevitable that gene flow will occur, albeit to very limited extents. If the result of that movement is of no major concern to crop management, health or the environment, then there can be little argument against the development of the trait in crop plants. In contrast to herbicide tolerance, a range of other traits are in development that seem unlikely to cause problems if gene flow occurs and will provide benefits to man. For many of these, if the traits move to other plants there will be no major adverse impacts. For example, a trait coding for the production of a particular oil is unlikely to impact adversely on related species or the environment. Nevertheless, regulatory testing will be required to examine the impact of new traits in organisms on food safety and the environment. Indirect effects and trophic interactions need to be considered, as in most cases the use of GMOs will be within agroecosystems. In evaluating the impact of pest resistance genes, for example, indirect interactions need to be considered. Proteins expressed in plants that affect crop herbivores, might in turn affect natural enemies of such pests. Nevertheless, a study on modified potato has found that a predator was not likely to be affected by a cysteine proteinase inhibitor from rice (Bouchard et al., 2003).

The particular trait that is considered should also be evaluated in the context it will be used. The context will have socio-economic dimensions, as well as environmental and technical aspects. GM crops designed for use in subsistence agriculture need to consider the longer term economic implications of their introduction. Cultural considerations may also be required. At this point, the question of the role of the profit motive as the guiding principle of development must be seriously questioned. To my mind there is likely to be conflict, even if commercial development has an element of altruism. As Pretty (2001) notes, "*There remain highly contrasting positions taken by different stakeholders over GMOs*". It seems obvious that the profit motive is behind the decisions to develop herbicide tolerance in crops, rather than weed tolerance.

With regard to biodiversity within agroecosystems, it is my view that there are means of matching the conservation of species with production. This may require the separation of most of production areas from conservation areas. Nevertheless, there are many species of plants animals and birds that have evolved with agriculture and are dependent on it. Such species can provide ecosystem functions and should be considered under the International Convention on Biodiversity, where such conditions are relevant. As noted by Beringer (2000) "*Nature and dense human populations cannot coexist without the former suffering. Our objective should be to develop and exploit our understanding of ecology to provide the information required to enable us to develop a far more enlightened future for agriculture and wildlife*". The challenge is to develop relevant farming systems for different environments, different climates and different societies. Each requires an appreciation of the multi-functionality of the farmed environment. GM technology should be able to contribute to those systems, so long as it is used wisely and is not regarded as the single answer to all agricultural advances.

REFERENCES

1. Anon (1994) Biodiversity. The UK Action Plan. HMSO, London. 187 pp.
2. Baillie, S.R., Crick, H.Q.P., Balmer, D.E., Bashford, R.I., Beaven, L.P., Freeman, S.N., Marchant, J.H., Noble, D.G., Raven, M.J., Siriwardena, G.M., Thewlis, R., & Wernhar, C.V. (2001). Breeding birds in the wider countryside: their conservation status 2000. Report No. 252. British Trust for Ornithology, Thetford, UK.
3. Barr, C.J., Bunce, R.G.H., Clarke, R.T., Fuller, R.M., Furse, M.T., Gillespie, M.K., Groom, G.B., Hallam, C.J., Hornung, M., Howard, D.C., & Ness, M.J. (1993). Countryside Survey 1990. Main Report. Department of the Environment.
4. Bartsch, D., Lehnen, M., Clegg, J., Pohl-Orf, M., Schuphan, I., & Ellstrand, N.C. (1999) Impact of gene flow from cultivated beet on genetic diversity of wild sea beet populations. Mol Ecol, 8, 1733-1741.
5. Beringer, J.E. (2000) Releasing genetically modified organisms: will any harm outweigh any advantage? J Appl Ecology, 37, 207-214.
6. Bouchard, E., Michaud, D., & Cloutier, C. (2003) Molecular interactions between an insect predator and its herbivore prey on transgenic potato expressing a cysteine proteinase inhibitor from rice. Mol Ecol, 12, 2429-2437.
7. Bradley, P.R., Johnson, W.G., Hart, S.E., Buesinger, M.L., & Massey, R.E. (2000) Economics of weed management in glufosinate-resistant corn (Zea mays L.). Weed Technology, 14, 495-501.
8. Breeze, V.G., Marshall, E.J.P., Hart, A., Vickery, J.A., Crocker, J., Walters, K., Packer, J., Kendall, D., Fowbert, J., & Hodkinson, D. (1999). Assessing pesticide risks to non-target terrestrial plants. A desk study. Commission PN0923. MAFF Pesticides Safety Directorate.
9. Buckelew, L.D., Pedigo, L.P., Mero, H.M., Owen, M.D.K., & Tylka, G.L. (2000) Effects of weed management systems on canopy insects in

herbicide-resistant soybeans. Journal of Economic Entomology, 93, 1437-1443.

10. Burn, A.J. (2000). Pesticides and their effects on lowland farmland birds. In Ecology and Conservation of Lowland Farmland Birds (eds N.J. Aebischer, A.D. Evans, P.V. Grice & J.A. Vickery), pp. 89-104. British Ornithologists' Union, Tring.
11. Campbell, L.H., Avery, M.I., Donald, P., Evans, A.D., Green, R.E., & Wilson, J.D. (1997). A review of the indirect effects of pesticides on birds. Report No. 227. Joint Nature Conservation Committee, Peterborough.
12. Caseley, J.C., Cussans, G.W., & Atkin, R.K., eds. (1991) Herbicide resistance in Weeds and Crops. Butterworth-Heinemann, Oxford.
13. Chamberlain, D.E. & Fuller, R.J. (2000) Local extinctions and changes in species richness of lowland farmland birds in England and Wales in relation to recent changes in agricultural land-use. Agriculture, Ecosystems & Environment, 78, 1-17.
14. Chamberlain, D.E., Fuller, R.J., Bunce, R.G.H., Duckworth, J.C., & Shrubb, M. (2000) Changes in the abundance of farmland birds in relation to the timing of agricultural intensification in England and Wales. Journal of Applied Ecology, 37, 771-788.
15. Colbach, N., Clermont-Dauphin, C., & Meynard, J.M. (2001a) GeneSys: a model of the influence of cropping system on gene escape from herbicide tolerant rapeseed crops to rape volunteers I. Temporal evolution of a population of rapeseed volunteers in a field. Agriculture, Ecosystems & Environment, 83, 235-253.
16. Colbach, N., Clermont-Dauphin, C., & Meynard, J.M. (2001b) GeneSys: a model of the influence of cropping system on gene escape from herbicide tolerant rapeseed crops to rape volunteers II. Genetic exchanges among volunteers and cropped populations in a small region. Agriculture, Ecosystems & Environment, 83, 255-270.

17. Conner, A.J., Glare, T.R., & Nap, J.-P. (2003) The release of genetically modified crops into the environment. Part II. Overview of ecological risk assessment. Plant J, 33, 19-46.
18. Cresswell, J.E., Osborne, J.L., & Bell, S.A. (2002) A model of pollinator-mediated gene flow between plant populations with numerical solutions for bumblebees pollinating oilseed rape. Oikos, 98, 375-384.
19. Dale, P.J. (2002) The environmental impact of genetically modified (GM) crops: a review. Journal of Agricultural Science, 138, 245-248.
20. Darmency & Fleury (2000) Mating system in Hirschfeldia incana and hybridization to oilseed rape. Weed Res, 40, 231-238.
21. Darmency, H., Lefol, E., & Fleury, A. (1998) Spontaneous hybridizations between oilseed rape and wild radish. Mol Ecol, 7, 1467-1473.
22. de Snoo, G.R. & de Wit, P.J. (1998) Buffer zones for reducing pesticide drift to ditches and risks to aquatic organisms. Ecotoxicology and Environmental Safety, 41, 112-118.
23. Desplanque, B., Hautekeete, N., & Van Dijk, H. (2002) Transgenic weed beets: possible, probable, avoidable? Journal of Applied Ecology, 39, 561-571.
24. Dewar, A.M., Haylock, L.A., Bean, K.M., & May, M.J. (2000) Delayed control of weeds in glyphosate-tolerant sugar beet and the consequences on aphid infestation and yield. Pest Management Science, 56, 345-350.
25. Dewar, A.M., May, M.J., Woiwod, I.P., Haylock, L.A., Champion, G.T., Garner, B.H., Sands, R.J.N., Qi, A., & Pidgeon, J.D. (2003) A novel approach to the use of genetically modified herbicide tolerant crops for environmental benefit. Proceedings of the Royal Society: Biological Sciences, 270, 335-340.
26. Dunwell, J.M. (1998) Novel food products from genetically modified crop plants: methods and future prospects. Int J Food Sci Tech, 33, 205-213.

27. Fagan, J., Schoel, B., Haegert, A., Moore, J., & Beeby, J. (2001) Performance assessment under field conditions of a rapid immunological test for transgenic soybeans. Int J Food Sci Tech, 36, 357-367.
28. Firbank, L.G., Heard, M.S., Woiwod, I.P., Hawes, C., Haughton, A.J., Champion, G.T., Scott, R.J., Hill, M.O., Dewar, A.M., Squire, G.R., May, M.J., Brooks, D.R., Bohan, D.A., Daniels, R.E., Osborne, J.L., Roy, D.B., Black, H.I.J., Rothery, P., & Perry, J.N. (2003) An introduction to the Farm-Scale Evaluations of genetically modified herbicide-tolerant crops. J Appl Ecology, 40, 2-16.
29. Fuller, R.J. (2000). Relationships between recent changes in lowland British agriculture and farmland bird populations: an overview. In The Ecology and Conservation of Lowland Farmland Birds (eds N.J. Aebischer, A.D. Evans, P.V. Grice & J.A. Vickery), pp. 5-16. British Ornithologists' Union, Tring.
30. Fuller, R.J., Gregory, R.D., Gibbons, D.W., Marchant, J.H., Wilson, J.D., Baillie, S.R., & Carter, N. (1995) Population declines and range contractions among farmland birds in Britain. Conservation Biology, 9, 1425-1441.
31. Greaves, M.P. & Marshall, E.J.P. (1987) Field margins: definitions and statistics. In Field Margins (eds J.M. Way & P.J. Greig-Smith), Vol. Monograph No. 35, pp. 3-10. British Crop Protection Council, Thornton Heath, Surrey, London.
32. Gueritaine, G., Bazot, S., & Darmency, H. (2003) Emergence and growth of hybrids between Brassica napus and Raphanus raphanistrum. New Phytol, 158, 561-567.
33. Hart, K. & Wilson, G.A. (1998) UK implementation of Agri-environment Regulation 2078/92/EEC: enthusiastic supporter or reluctant participant? Landscape Research, 23, 255-272.
34. Hauser, Jørgensen, & Ostergård (1998) Fitness of backcross and F2 hybrids between weedy Brassica rapa and oilseed rape(B. napus). Heredity, 81, 436-443.

35. Hudson, L.C., Chamberlain, D., & Stewart, C.N. (2001) GFP-tagged pollen to monitor pollen flow of transgenic plants. Mol Ecol Notes, 1, 321-324.
36. Kim, K.U. (2001) Trends and expectations for research and technology in the Asia-Pacific region. Weed Biol Manage, 1, 20-24.
37. Kleijn, D. & Snoeijing, G.I.J. (1997) Field boundary vegetation and the effects of agrochemical drift: botanical change caused by low levels of herbicide and fertilizer. Journal of Applied Ecology, 34, 1413-1425.
38. Kleijn, D. & Sutherland, W.J. (In press) How effective are agri-environment schemes in conserving and promoting biodiversity? Journal of Applied Ecology.
39. Kudsk, P. & Streibig, J.C. (2003) Herbicides - a two-edged sword. Weed Res, 43, 90-102.
40. Kuiper, H.A., Kleter, G.A., Noteborn, H.P.J.M., & Kok, E.J. (2001) Assessment of the food safety issues related to genetically modified foods. Plant J, 27, 503-528.
41. Kwon, Y.W. & Kim, D.-S. (2001) Herbicide-resistant genetically-modified crop: its risks with an emphasis on gene flow. Weed Biol Manage, 1, 42-52.
42. Kwon, Y.w., Kim, D.S., & Yim, K.-O. (2001) Herbicide-resistant genetically modified crop: assessment and management of gene flow. Weed Biol Manage, 1, 96-107.
43. Lefol, E., Danielou, V., Darmency, H., Boucher, F., Maillet, J., & Renard, M. (1995) Gene dispersal from transgenic crops. I. Growth of interspecific hybrids between oilseed rape and the wild hoary mustard. Journal of Applied Ecology, 32, 803-808.
44. Longley, M., Cilgi, T., Jepson, P.C., & Sotherton, N.W. (1997) Measurements of pesticide spray drift deposition into field boundaries and hedgerows .1. Summer applications. Environmental Toxicology and Chemistry, 16, 165-172.

45. Longley, M. & Sotherton, N.W. (1997a) Factors determining the effects of pesticides upon butterflies inhabiting arable farmland. Agriculture Ecosystems & Environment, 61, 1-12.
46. Longley, M. & Sotherton, N.W. (1997b) Measurements of pesticide spray drift deposition into field boundaries and hedgerows .2. Autumn applications. Environmental Toxicology and Chemistry, 16, 173-178.
47. Lutman, P.J.W. & Berry, K. (2003) Herbicide-tolerant crops - good or bad for Europe? Outlook on Agriculture, 32, 91-95.
48. Marchis, F.D., Bellucci, M., & Arcioni, S. (2003) Measuring gene flow from two birdsfoot trefoil (Lotus corniculatus) field trials using transgenes as tracer markers. Molecular Ecology, 12, 1681.
49. Marlander, B., Hoffmann, C., Koch, H.-J., Ladewig, E., Merkes, R., Petersen, J., & Stockfisch, N. (2003) Environmental Situation and Yield Performance of the Sugar Beet Crop in Germany: Heading for Sustainable Development. J Agron Crop Sci, 189, 201-226.
50. Marrs, R.H., Frost, A.J., Plant, R.A., & Lunnis, P. (1993) Determination of buffer zones to protect seedlings of nontarget plants from the effects of glyphosate spray drift. Agriculture Ecosystems & Environment, 45, 283-293.
51. Marshall, E.J.P. (1987). Herbicide effects on the flora of arable field boundaries. In 1987 British Crop Protection Conference - Weeds, pp. 291-298. British Crop Protection Council, Thornton Heath, Surrey, Brighton, UK.
52. Marshall, E.J.P. (2001) Biodiversity, herbicides and non-target plants. In Pesticide Behaviour in Soils and Water. BCPC Monograph No. 78 (ed A. Walker), pp. 419-426. BCPC, Farnham, UK, Brighton, UK.
53. Marshall, E.J.P. (2002) Introducing field margin ecology in Europe. Agriculture Ecosystems & Environment, 89, 1-4.
54. Marshall, E.J.P. (In press). Field margins in northern Europe: integrating agricultural, environmental and biodiversity functions. In Topics in

Canadian Weed Science. Field Boundary Habitats: Implications for weed, insect and disease management (ed A.G. Thomas), Vol. 1.

55. Marshall, E.J.P., Brown, V.K., Boatman, N.D., Lutman, P.J.W., Squire, G.R., & Ward, L.K. (2003) The role of weeds in supporting biological diversity within crop fields. Weed Res, 43, 77-89.

56. Marshall, E.J.P. & Moonen, A.C. (2002) Field margins in northern Europe: their functions and interactions with agriculture. Agriculture Ecosystems & Environment, 89, 5-21.

57. Marshall, E.J.P. & Moonen, C. (1998). A review of field margin conservation strips in Europe. A report for the UK Ministry of Agriculture, Fisheries and Food. 92 pp. IACR - Long Ashton Research Station, Bristol.

58. Marshall, J., Brown, V., Boatman, N., Lutman, P., & Squire, G. (2001). The impact of herbicides on weed abundance and biodiversity. PN0940. A report for the UK Pesticides Safety Directorate. IACR-Long Ashton Research Station. 134 pp.

59. May, M.J. (2003) Economic consequences for UK farmers of growing GM herbicide tolerant sugar beet. Annals of Applied Biology, 142, 41-48.

60. Moonen, A.C. & Marshall, E.J.P. (2001) The influence of sown margin strips, management and boundary structure on herbaceous field margin vegetation in two neighbouring farms in southern England. Agriculture, Ecosystems & Environment, 86, 187-202.

61. Moreby, S.J. & Southway, S.E. (1999) Influence of autumn applied herbicides on summer and autumn food availability to birds in winter wheat fields in southern England. Agriculture, Ecosystems & Environment, 72, 285-297.

62. Moyes, C.L., Lilley, J.M., Casais, C.A., Cole, S.G., Haeger, P.D., & Dale, P.J. (2002) Barriers to gene flow from oilseed rape (Brassica napus) into populations of Sinapis arvensis. Mol Ecol, 11, 103-112.

63. Nakayama, Y. & Yamaguchi, H. (2002) Natural hybridization in wild soybean (*Glycine max* ssp. *soja*) by pollen flow from cultivated soybean

(*Glycine max* ssp. *max*) in a designed population. Weed Biol Manage, 2, 25-30.
64. Nishiura, H., Imai, H., Nakao, H., Tsukino, H., Kuroda, Y., & Katoh, T. (2002) Genetically modified crops: consumer attitudes and trends in plant research in Japan. Food Serv Technol, 2, 183-189.
65. Orson, J. (2001). Gene stacking in herbicide tolerant oil seed rape: lessons from the North American experience. English Nature, Peterborough.
66. Paoletti, M.G., Pimentel, D., Stinner, B.R., & Stinner, D. (1992) Agroecosystem biodiversity - matching production and conservation biology. Agriculture, Ecosystems & Environment, 40, 3-23.
67. Perlak, F.J., Oppenhuizen, M., Gustafson, K., Voth, R., Sivasupramaniam, S., Heering, D., Carey, B., Ihrig, R.A., & Roberts, J.K. (2001) Development and commercial use of Bollgard® cotton in the USA - early promises versus today's reality. Plant J, 27, 489-501.
68. Perry, J.N. (2002) Sensitive dependencies and separation distances for genetically modified herbicide-tolerant crops. Proceedings of the Royal Society: Biological Sciences, 269, 1173-1176.
69. Perry, J.N., Rothery, P., Clark, S.J., Heard, M.S., & Hawes, C. (2003) Design, analysis and statistical power of the Farm-Scale Evaluations of genetically modified herbicide-tolerant crops. J Appl Ecology, 40, 17-31.
70. Pidgeon, J.D., M., D.A., & J., M.M. (2001) Weed management for agricultural and environmental benefit in GMHT sugar beet. In Brighton Crop Protection Conference Weeds, pp. 373-382.
71. Pierre, J., Marsault, D., Genecque, E., Renard, M., Champolivier, J., & Pham-Delegue, M.H. (2003) Effects of herbicide-tolerant transgenic oilseed rape genotypes on honey bees and other pollinating insects under field condtions. null, 108, 159-168.
72. Pretty, J. (2001) The rapid emergence of genetic modification in world agriculture: contested risks and benefits. Environmental Conservation, 28, 248-262.

73. Reddy, K.N. (2001) Glyphosate-resistant soybean as a weed management tool: Opportunities and challenges. Weed Biol Manage, 1, 193-202.
74. Richter, O., Zwerger, P., & Bottcher, U. (2002a) Modelling spatio-temporal dynamics of herbicide resistance. Weed Res, 42, 52-64.
75. Richter, O., Zwerger, P., & Böttcher, U. (2002b) Modelling spatio-temporal dynamics of herbicide resistance. Weed Research, 88, 52-64.
76. Robinson, S., Scott, N., & Gackle, A. (2000) Gene technology and future foods. Asia Pac J Clin Nutr, 9, S113-S118.
77. Rognli, O.A., Nilsson, N.-O., & Nurminiemi, M. (2000) Effects of distance and pollen competition on gene flow in the wind-pollinated grass Festuca pratensis Huds. Heredity, 85, 550-560.
78. Saeglitz, C., Pohl, M., & Bartsch, D. (2000) Monitoring gene flow from transgenic sugar beet using cytoplasmic male-sterile bait plants. Mol Ecol, 9, 2035-2040.
79. Siriwardena, G.M., Baillie, S.R., Crick, H.Q.P., & Wilson, J.D. (2000) The importance of variation in the breeding performance of seed-eating birds in determining their population trends on farmland. Journal of Applied Ecology, 37, 128-148.
80. Siriwardena, G.M., Baillie, S.R., Crick, H.Q.P., & Wilson, J.D. (2001) Changes in agricultural land-use and breeding performance of some granivorous farmland passerines in Britain. Agriculture, Ecosystems & Environment, 84, 191-206.
81. Song, Z., Lu, B., Zhu, Y., & Chen, J. (2002) Pollen competition between cultivated and wild rice species (*Oryza sativa* and *O. rufipogon*). New Phytol, 153, 289-296.
82. Steinbrecher, R.A. (1996) From green to gene revolution: the environmental risks of genetically engineered crops. Ecologist, 26, 273-281.
83. Tahvanainen, L., Ihalainen, M., Hietala-Koivu, R., Kolehmainen, O., Tyrvainen, L., Nousiainen, I., & Helenius, J. (2002) Measures of the EU Agri-Environmental Protection Scheme (GAEPS) and their impacts on the

visual acceptability of Finnish agricultural landscapes. Journal of Environmental Management, 66, 213-227.

84. Tester, M. (2001) Depolarizing the GM debate. New Phytol, 149, 9-12.
85. Thompson, C.J., Thompson, B.J.P., Ades, P.K., Cousens, R., Garnier-Gere, P., Landman, K., Newbigin, E., & Burgman, M.A. (2003) Model-based analysis of the likelihood of gene introgression from genetically modified crops into wild relatives. Ecological Modelling, 162, 199-209.
86. Watkinson, A.R., Freckleton, R.P., Robinson, R.A., & Sutherland, W.J. (2000) Predictions of biodiversity response to genetically modified herbicide-tolerant crops. Science, 289, 1554-1557.
87. Wilson, A., Seavers, G.P., & Wright, K.J. (1999) An investigation into the allelopathic potential of oats (*Avena sativa*). In Proceedings 11th EWRS Symposium, pp. 73. EWRS, Basel.
88. Wilson, P.J. (1990) The ecology and conservation of rare arable weed species and communities. Ph.D., Southampton, Southampton.
89. Wilson, P.J. (1993). Conserving Britain's cornfield flowers. In 1993 Brighton Crop Protection Conference - Weeds, Vol. 1, pp. 411-416. British Crop Protection Council, Brighton.

Table 1. Area of GM crops by country 1999-2001 (data from James, 2001).

	Total area (million ha)		
Country	1999	2000	2001
USA	28.7	30.3	35.7
Argentine	6.7	10.0	11.8
Canada	4.0	3.0	3.2
China	0.3	0.5	1.5
South Africa	0.1	0.2	0.2
Australia	0.1	0.2	0.2
Romania	<0.1	<0.1	<0.1
Mexico	<0.1	<0.1	<0.1
Bulgaria	-	<0.1	<0.1
Spain	<0.1	<0.1	<0.1
Germany	-	<0.1	<0.1
France	<0.1	<0.1	-
Uruguay	-	<0.1	<0.1
Indonesia	-	-	<0.1
Total	39.9	44.2	52.6

Note: in addition to these countries, GM carnations have also been grown in the Netherlands, Japan, Ecuador and Columbia

Table 2. Risks of genetic modifications within agricultural systems (Pretty, 2001).

	Risk
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
7	antibiotic resistance marker genes

Table 3. Percentage changes in farmland bird populations between 1974 and 1999 recorded in the British Trust for Ornithology Common Bird Census plots in the UK. Taken from: http://www.bto.org/birdtrends/appendix71b.htm#cbcfarm25

Species	**Plots (n)**	**Change (%)**	**Lower limit**	**Upper limit**	**Comment**
Linnet	73	-46	-58	-30	
Lapwing	38	-45	-69	-31	Unrepresentative
Moorhen	55	-43	-52	-29	
Treecreeper	29	-42	-68	-11	
Yellowhammer	73	-42	-53	-32	
Dunnock	93	-40	-51	-27	
Goldcrest	27	-37	-54	-6	
Blackbird	96	-34	-41	-27	
Cuckoo	50	-26	-45	-2	
Tree Sparrow	34	-93	-97	-86	
Corn Bunting	17	-90	-95	-80	Small sample
Grey Partridge	40	-83	-88	-77	
Turtle Dove	25	-81	-90	-67	
Spotted Flycatcher	31	-75	-86	-60	
Bullfinch	47	-71	-79	-61	
Snipe	7	-70	-96	-53	Small sample
Song Thrush	82	-66	-73	-57	
Redshank	9	-60	-82	-19	Small sample
Reed Bunting	49	-58	-71	-44	
Starling	65	-55	-68	-38	
Skylark	83	-54	-60	-44	
Mistle Thrush	59	-51	-61	-43	

Table 4. Separation distances advised for GMHT crops in the UK http://www.ukasta.org.uk/scimac/guidelines.pdf

Crop type	Certified seed (same species)	Registered organic crops (same species)	Non-GM crops (same species)
Oilseed rape	200m	200m	50m
Sugar beet	600m	600m	6m
Fodder beet	600m	600m	6m
Forage maize	200m	200m	200m sweetcorn 50m forage maize

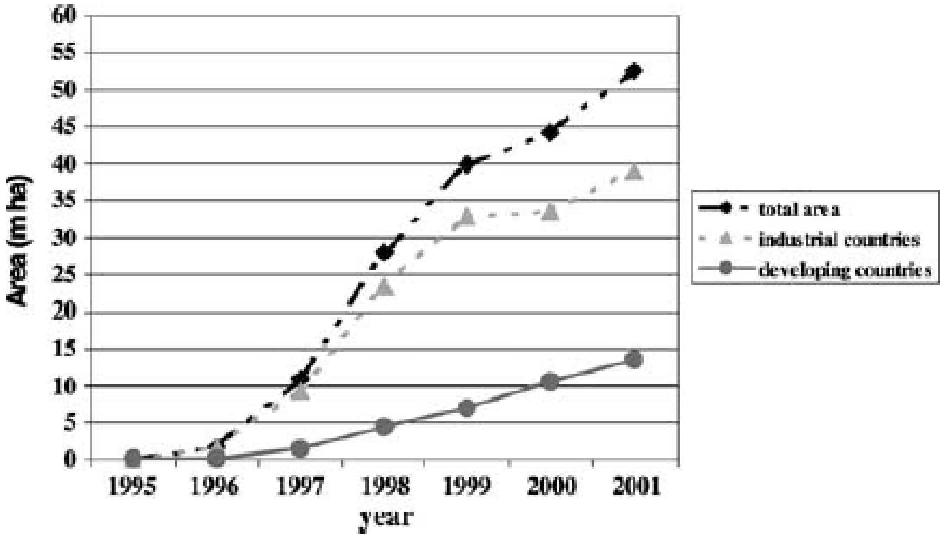

Fig. 1. Area of transgenic crops grown in the world, 1995-2001. James, C. (2001) Global Review of Commercialised Transgenic Crops: 2001. ISAAA Briefs no. 24: Preview. Ithaca, NY: International Service for the Acquisition of Agri-Biotech Applications. (http://www.isaaa.org/publications/briefs/Brief_24.htm).

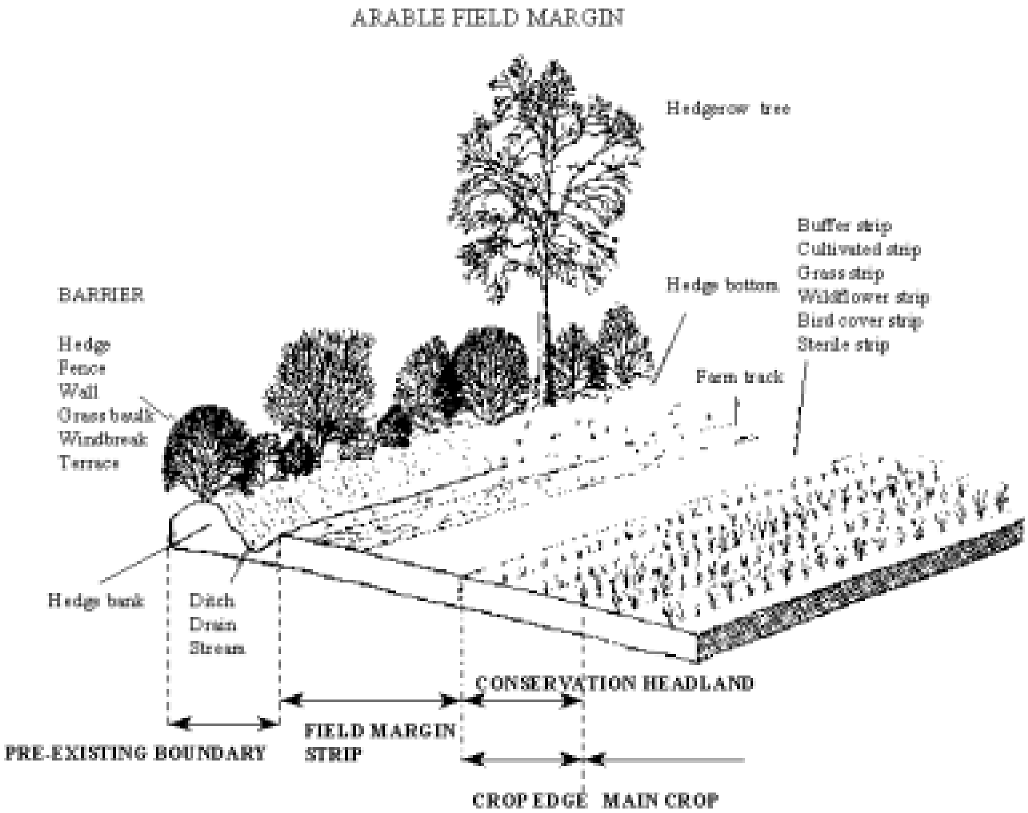

Fig. 2. A stylised field margin showing the location of a field margin strip that can act as a buffer. After Greaves & Marshall (1987).

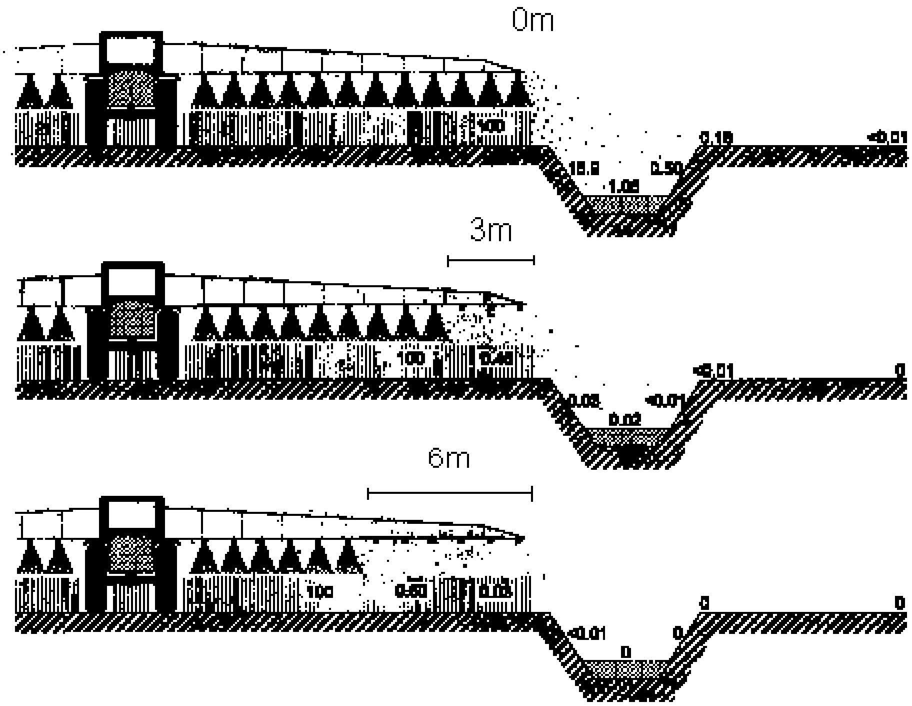

Fig. 3. Percentages (%) of field rate spray deposition with 0, 3m and 6m no-spray zones adjacent to a watercourse in the Netherlands. After de Snoo & de Wit (1998).