GM SCIENCE REVIEW

FIRST REPORT

An open review of the science relevant to GM crops and food based on the interests and concerns of the public

PREPARED BY THE GM SCIENCE REVIEW PANEL (JULY 2003)

Chapter 6

ENVIRONMENTAL IMPACTS OF GM CROPS

6.1 INTRODUCTION

This chapter of the GM Science Review report considers the state of our current scientific knowledge on the issues of public and professional concern associated with how GM plants behave in the environment and the impacts they may have. The focus is on the possible direct and indirect environmental impacts arising from the GM crops themselves and not other crop varieties or related plants that might have acquired the transgene as a result of gene flow. Gene flow mediated impacts are covered in Chapter 7 on Gene Flow.

Public concerns about GM were reflected in the report of the 'Review of Public Concerns', produced as a result of a series of 'foundation discussion workshops' conducted by Corr Willbourn Research and Development under the GM Public Debate strand of the GM Dialogue.

More specifically, issues related to the Environmental Impacts of GM crops were raised under the Review at the various Open meetings, as contributions to the Review website, and by GM Science Review Panel members at their meetings.

Seven key areas were identified and are considered in this chapter.

6.2 Invasiveness/ Persistence
Could GM plants be invasive or persistent, and what might be the impacts?

6.3 Toxicity to Wildlife
Could GM plants be toxic to wildlife, and what might be the impacts?

6.4 Development of Resistance
Could crops engineered with novel resistance genes lead to the emergence of new forms of pests, diseases and weeds that are resistant to chemical sprays? Will new forms of insects and diseases evolve which are able to bypass GM resistance genes?

6.5 Changes in weed control strategies
Will herbicide tolerant crops offer new weed control strategies and, if so, what are the likely impacts, positive and negative? What are the real benefits of HT crops, and what will their effect on biodiversity be?

6.6 Horizon Scanning
Apart from HT crops what are the traits that might give rise to significant environment impacts, positive or negative?

6.7 Changes to agricultural practices

Might GM crops significantly change agricultural practice in the UK? If so, what might be the consequences?

6.8 Limitations of Science

Is the science available to predict the environmental impacts of GM plants?

6.2 INVASIVENESS / PERSISTENCE OF GM PLANTS

Could GM plants become invasive or persistent and what might be the impacts?

6.2.1. Summary

There is a conjectural risk that genetically modified crop plants might be more invasive of natural habitats than their conventional counterparts. Not withstanding the case-by-case approach taken by the regulatory authorities in evaluating invasiveness, there are two principal models that have been influential in considering the potential for GM crops to become more invasive of natural habitats than their conventional counterparts. One is the Alien Species Model. The hypothesis is that roughly 0.1% of introduced GM plants would become pests, because that was the rate of invasive alien plants species (c. 15 problem plants out of an estimated 15,000 species introduced). The other is the Crop Model, which argues that GM crops will behave in much the same way as conventional crop plants except for the GM trait that may influence fitness.

Evidence from the PROSAMO[1] experiments indicates that the Alien Species Model may provide a poor estimate of the probability of the GM crops used in the experiments becoming invasive. Well replicated field experiments on GM HT oilseed rape, sugar beet, and maize, and GM insect resistant potato showed that these GM plants were not more invasive or more persistent than their conventional counterparts. This suggests that the crop model is likely to be more predictive of the behaviour of the GM plants used in these experiments than the Alien Species Model.

Therefore, for some GM crops and constructs the probability of a problem arising is lower, and the environmental consequences are less severe than predicted by the Alien Species Model. However, in future, it is likely that the trend in transgenics will be to produce crops that are better adapted to biotic and abiotic conditions found on agricultural landscapes. These crops will need less human intervention to survive and thrive. By definition, because they are better adapted to harsher environments, they may be more able to persist and become invasive. The probability of invasion might be expected to be closer to the Alien Species Model. However, many domesticated crops are selected for traits that give them a disadvantage in the wild (e.g. big seeds, non-dehiscing pods, high nutrient requirements) which may limit their fitness outside cultivation.

For unfamiliar crops and constructs, invasiveness needs to be examined on a case-by-case basis, and the only reliable evidence is likely to come from field experiments.

6.2.2 Background

The alien species concept on invasiveness has a long history (Elton, 1958), and the consequences of plant invasions are well documented (Drake *et al.* 1989; Pysek *et al.* 1995; Simberloff *et al*. 1997). The Crop Model is a more recent concept, and was developed in the context of the PROSAMO experiment (Planned Release of Selected and Modified

[1] Planned Release of Selected and Modified Organisms (PROSAMO). These experiments studied genetically modified rape, maize and sugar beet that were herbicide tolerant and potatoes that expressed the insecticidal *Bt* gene.

Organisms) which compared the ecology of conventional and GM HT rape, maize and sugar potatoes that expressed the insecticidal *Bt* gene in a range of natural habitats (Crawley *et al.* 1993, 2001). The Crop Model assumes that some GM crops, especially those that exhibit traits that would not be expected to increase fitness in semi-natural habitats, behave like the non-GM crop with respect to invasiveness. Concerns regarding invasive species were the subject of one website contribution [2]. This subject was also addressed at the Royal Society meeting [3].

The relationship between the biological traits of a plant species and the likelihood that a species becomes invasive when introduced into a new habitat is complex, and all the evidence suggests that invasive potential cannot be predicted on the basis of traits alone (all plant species are capable of rapid increase in abundance under the right conditions; Crawley *et al.* 1996). The only reliable predictor of whether or not an introduced species will become invasive is whether it is known to have been invasive in other places (Veltman *et al.* 1996). There was a view that weediness was predictable on the basis of plant traits. For example, the attributes of the 'ideal weed' were listed (Baker, 1965), but it turns out that the traits of weediness identified by Baker have absolutely no power in predicting whether or not a species will be invasive when it is introduced into a new environment (Williamson, 1993).

6.2.3 Range of Views and Quality of Evidence

The PROSAMO programme studied genetically modified rape, maize and sugar beet that were herbicide tolerant and potatoes that expressed the insecticidal *Bt* gene. The survival was shown to be about 3%. After 10 years, there were no rape plants remaining. Maize never survived longer than a year and the longest-lived sugar beet was 2 years (Crawley *et al.* 2001).

For a plant to increase from a low frequency to become persistent or invasive in a non-target habitat, it must go through several stages. It must first escape from the location where it is cultivated, become established and survive to reproductive stage, producing viable seeds or vegetative propagules that form a second generation. For the population to increase in abundance they must leave, on average, one mature descendent. These stages are considered below.

Presence of GM plants outside arable fields

Is the mere presence of an individual GM plant a problem?

Yes, if it was a source of noxious products (pollen, seed, leaves, allelopathic or toxic chemicals) or attracted to it and subsequently harmed beneficial organisms (e.g. toxic foliage or nectar, tainted pollen). But there is no evidence for such effects in GM HT crops studied so far.

Many plants with noxious properties are grown without harm to people or the environment in agriculture, gardens and arboreta, and several familiar plants have poisonous seeds, leaves or fruits (laburnum, potato, rhubarb, etc.).

[2] GM Science Review Website. Cates 2003 http://www.gmsciencedebate.org.uk/topics/forum/0015.htm
[3] Royal Society meeting. Crawley 2003 http://www.gmsciencedebate.org.uk/meetings/pdf/110203-speakers.pdf

Introduction of seeds or vegetative propagules

What is the chance of GM plants escaping into non-target habitats?

Escape of plants from cultivation or from spillage in transit is almost certain to occur. Most crop plants are recorded outside arable fields in most parts of Britain (Crawley, 1987).

GM plants are likely to be of concern only if they increase in abundance once they have arrived at a location. However, constant recruitment does have the ability to produce large populations. Large ephemeral populations from seed transport and spillage could produce problems in agricultural landscape e.g. weed beet populations are proving problematic for growers and breeders in France and the Czech Republic (Bartsch *et al*. 1999; Soukup *et al*. 2002). The mere fact of increasing in abundance does not necessarily constitute a "problem" if there are no negative impacts associated with this increase.

Establishment of first generation individuals from these propagules

Will GM escapes become established?

It depends upon the habitat into which they are introduced. The Parable of the Sower (Matthew 13:4) is worth recalling here: “some seeds fell by the wayside, and the fowls came and devoured them up: Some fell upon stony places, where they had not much earth: and forthwith they sprung up, because they had no deepness of earth: And when the sun was up they were scorched; and because they had no root they withered away. And some fell among thorns; and the thorns sprung up, and choked them: But others fell into good ground, and brought forth fruit, some an hundred fold, some sixty fold, some thirty fold”. This catalogues the hazards facing a seed (predation, unsuitable microsites, plant competition). A major problem with predicting invasiveness is the difficulty of predicting which (if any) habitat an invader will colonise, so assessing the performance of a novel phenotype (which is always relative to a habitat/community) in the context of invasiveness is almost impossible with our present state of ecological knowledge.

Establishment is more likely in some habitats than others and in some successional stages. In the UK, seedlings of crop plants are common on disturbed open ground in towns, in arable land and on open roadsides, and rare or absent in closed grasslands and woodlands. Early successional habitats, with much open ground, and typically low levels of interspecific plant competition, are more likely to support crop seedlings than late successional closed vegetation. There may be GM plants in future (e.g. trees) with seeds sufficiently large that they are capable of establishment in late successional vegetation, but current GM crops show no such tendencies (Stace, 1997). In the future, GM herbicide tolerant or high yielding grasses could be capable of invading semi-natural grasslands (pasture, golf-courses, parks) and possibly other habitats, especially if they exhibited small increases in fitness because specific herbicides were used periodically on these areas.

Survival to reproductive age or size

Will GM seedlings grow to reproductive size?

This depends almost entirely on the habitat in which the seedlings are established. The greatest threat to the young plant is competition from established plants (shading, exploitation of soil water or nutrients). Plants surviving competition may be eaten by herbivores and either killed directly, weakened so that they succumb to plant competition, or kept at a size below the threshold for reproduction.

In the PROSAMO experiments, GM plants of oilseed rape, sugar beet, potato and maize all grew to reproductive size in one or more of the 12 natural habitats (woodlands, grassland, waste ground, heathland, wetland etc.) distributed over Britain (Crawley *et al*. 2001). It is possible therefore for some escaped GM plants to grow large enough to reproduce, at least in some habitats.

Reproduction (production of seed or vegetative propagules)

Will GM plants produce viable seeds or vegetative propagules outside arable cultivation?

In addition to the ecological effects mentioned above, reproduction may require the presence of other individuals to ensure cross pollination for plants that are not self compatible. In addition, pollination may require the services of more or less specialized pollinating animals (e.g. bees or moths). Absence or shortage of such mutualists might reduce the rate of seed production per plant.

In the PROSAMO experiments, GM HT plants of oilseed rape, sugar beet and insect resistant potato produced viable seed in one or more of the 12 natural habitats distributed over Britain (Crawley *et al.* 2001), but GM HT maize did not produce viable seed at any of the locations. Nevertheless, the evidence suggests that we should assume that GM crops would produce viable seed or vegetative propagules (e.g. potato tubers), at least in some habitats.

Dispersal and recruitment

Will GM plants form a second generation by dispersal and recruitment from escaped parent plants?

Just as introduced seed can produce recruits (see above) then so, in principle, could seed dispersed from established escapes.

In the PROSAMO experiments, GM HT plants of oilseed rape and sugar beet produced second-generation plants in one or more of the 12 natural habitats distributed over Britain (Crawley *et al.* 2001), but GM insect resistant potato and HT maize did not. The evidence suggests that we should assume that at least some GM crops will produce second generation plants following escape from agriculture, at least in some habitats. The key point is the number of such second generation (and subsequent generation) plants produced per parent plant (see below).

Formation of a self replacing population

Will GM plants increase in abundance following escape from arable culture?

All plants exhibit the potential to increase in abundance under appropriate conditions, “some an hundred fold, some sixty fold, some thirty fold”. The ability to increase when rare is a fundamental ecological trait, known as the “invasion criterion”. Technically, it requires that population change must be positive when plant density is low. We would not expect a large population of plants to go on increasing (e.g. because of competition for space), so there is no requirement for increase in large populations.

Will escaped GM plants leave more than one mature descendent on average (i.e. will populations tend to increase in abundance)?

In the PROSAMO experiments, none of the GM plants of oilseed rape, sugar beet, potato or maize increased in abundance in any of the 12 natural habitats distributed over Britain (Crawley *et al.* 2001). All the GM crops (and their conventional counterparts) failed the invasion criterion, and declined to extinction within 1 – 4 years (non-GM potato survived more than 10 years at one site). In all cases, failure to pass the invasion criterion was due to the combined effects of plant competition and herbivore attack. Thus, while it is possible in principle for GM crop plants to increase in abundance following escape from arable cultivation, the evidence suggests that this will not occur in any of the habitats so far investigated (woodlands, grassland, waste ground, heathland, wetland etc.), for the GM crops currently available.

A ten-year study addressing the question of whether arable crops are invasive of adjacent natural habitats showed that the population of the crop in the natural habitat was seed limited. The study focused on *Brassica napus* subspecies *olifera* (oil seed rape) on both verges of the 189 kilometres of the M25 London orbital motorway and provides a model system for the ecology of crop plants that grow outside arable fields (Crawley & Brown 1995). This study showed that there was no evidence that oil seed rape is invasive of adjacent semi-natural habitats, despite the fact that it is known to persist for long periods in disturbed habitats.

In principle, however, transgenes which confer a clear fitness advantage on a GM crop plant (for example insect-resistance or drought tolerance, rather than simply herbicide tolerance) might enhance their performance outside of arable fields. Such traits require case-by-case field testing for invasiveness and it would be unwise to generalise from GM HT plants to all other transgene constructs.

Increase in abundance to problem status

Will GM crops become problem plants?

It can be argued that if the mere presence of GM plants outside arable cultivation is not in itself a problem (see above), then GM crops would only become a problem if they were to increase in abundance.

Evidence to date, for current GM crop species and current GM constructs like herbicide tolerance (for oil seed rape, sugar beet and maize) or insect resistance in potato, indicates clearly that GM crops will not become problem plants following escape from cultivation. This evidence is strong, based as it is on long-term widespread replicated field experiments.

We need to be circumspect, of course, about future transformed plant species and novel GM constructs that might be expected to increase plant fitness under field conditions. It is possible, however, that fitness-affecting GM constructs will involve trade-offs of one sort or another. Traits that enhance fitness in one habitat may have exactly the reverse effect in another habitat. Only field testing is likely to provide definitive answers to these questions.

Critique of the Alien Species Model

The Alien Species Model to predict the invasive ability of GM plants is a simple analogy with the invasiveness of alien plant species. The hypothesis is that roughly 0.1% of introduced

GMs would become pests, because that was the rate of invasive alien plants species (c. 15 problem plants out of an estimated 15,000 species introduced; Crawley, 1987; Williamson, 1993). However, the risks of a GM crop being invasive cannot based on probabilities like this, but on the nature of the transgene(s) that has been inserted. Multi-trait transformations could be used to increase fitness of the crop in agricultural habitats, thereby increasing the probability of invasiveness of disturbed habitats.

The Alien Species Model is good in that it shows the extent of the problem should it happen, but overstates the risks (in particular, the *probability* that a GM crop will become invasive) associated with the current GM constructs and crops. Alien invaders have attributes which are quite different to the attributes of the crops which are currently GM. They are usually thicket forming perennials, which are horticultural rather than arable species.

6.2.4 Is there general scientific agreement?

The PROSAMO experiments comparing GM HT oil seed rape, maize and sugar beet and insect resistant potato crop plants with non-GM crops plants demonstrate convincingly that the GM plants studied were not more invasive or more persistent in semi-natural habitats, and provide convincing evidence that GM itself does not make these plants more invasive. Escaped plants of all crop species are found throughout those parts of Britain where the crops are grown; these are known as ‘casual species’, and none of them is regarded as being a problem in semi-natural habitats.

The scientific consensus is that, at present, there is no evidence that the GM crops currently available for commercial use in Europe, would be more invasive than their non-GM counterparts if released into the environment, or that gene flow from them will generate more invasive populations of wild relatives (see 7.3). There is, though, considerable uncertainty as to the invasiveness of GM crops with fitness enhancing traits such as resistance to abiotic stress.

6.2.5 Is the issue unique to GM?

The possibility of ‘alien’ species becoming invasive is a reality as is clearly shown by non-native plants being brought into the UK (Crawley *et al.* 1996). An example of this is *Rhododendron ponticum* which is invasive of shaded native woodland and has caused the massive loss of biodiversity, especially ferns and mosses. Other examples are *Buddleja davidii, Mimulus guttatus, Impatiens glandulifera* and *Fallopia japonica.* These species have become invasive in the UK because they have found a niche not previously occupied or have superior competitive ability compared with the native species. The fact that more than 1,200 alien species (see box 6.1) are present in Britain, draws attention to the fact that mere presence of alien species is not itself a problem. We estimate that about 15,000 alien species capable of growing under British climatic conditions have been introduced (intentionally or unintentionally) and only about 15 species have increased in abundance to the point at which they are considered to be a problem. However, it is difficult to get two people to agree about what constitutes a weed – a plant in the wrong place is the standard definition (Naylor & Lutman, 2002), but Mark Twain had a different perspective when he defined a weed as “a plant whose virtues have yet to be discovered”).

The issue is unique to GM in that GM techniques enable traits to be put into crop plants that may not occur through evolution or conventional breeding. This fact is the reason that a regulatory system has been constructed around GM crops to require consideration of whether those crop/trait combinations might lead to undesirable environmental impacts, including invasiveness. Although this shows that a GM plant could theoretically become invasive, there is general agreement that equating current GM crops to exotic plants provides a very limited model for predicting the effects of gene flow and GM crops. This is due to a difference in biology and life history of these problematical 'alien invaders' and GM crops. The most common alien invaders tend to be thicket-forming woody perennials which have unfamiliar genotypes. The GM crops tend to be herbaceous annuals that are genetically close to familiar crops and have been studied and improved for use in agriculture over many years by selecting traits very different to weeds, demanding significant inputs and husbandry. However, the potential for invasiveness has to be considered crop by crop and trait by trait. If genetic modification was applied to potentially more invasive plant species, or the traits put into crop plants conferred significant advantages in terms of survival beyond the agricultural environment (salt tolerance is one example), the possibility of 'alien species' behaviour would have to be carefully investigated.

In the future GM plants may not be comparable with non-GM, because transgenic technology may have the ability to fundamentally change the physical and reproductive architecture and metabolism of crop plants to the point where they could effectively become new species. For these plants comparison with alien species may be more useful for assessing their invasive potential.

Box 6.1

Numbers of species and subspecies in the flora of Great Britain

Sexual species	1698
Agamospecies*	806
Total Native	**2504**
Naturalized Aliens	1274
Subtotal	**3778**
Casuals	c.3138
Total	**6916**

***** Numbers of agamospecies refer to those in the genera *Hieracium, Rubus* and *Taraxacum* only.
Source: Table from C Stace, 2002

6.2.6 Are there important gaps in out knowledge or scientific uncertainties and are these important?

We do not have an exact understanding of what changes in a plant's life history will affect its invasiveness.

More knowledge on the potential effects of releasing GM plants with traits such as virus resistance and drought and salt tolerance is required (see Chapter 7.3). In particular, we need to know how plants control traits such as growth rate, longevity, plant size, or survivorship in crops and plant species with potentially more invasive life histories (e.g. woody plants,

perennial grasses, thicket-forming herbs), and apply this knowledge to understanding effects in GM crops.
Further research should also focus on potential invasiveness in farmland habitats where, for example, herbicides and fertilisers are used, and periodic disturbance is a characteristic feature.

One of the difficulties of risk assessment is that invasiveness can take many generations of the plant to emerge, and may involve hybridisation with related species.

6.2.7 Likely future developments

As GM technologies are applied to a wider range of plants, the review of their potential to become invasive will need to be applied on a case-by-case basis (this case-by-case assessment of invasiveness is already carried out for each crop, and is also part of the regulatory approval process). Plants with large seeds such as trees, patch-forming pasture grasses, or crops with resistance to key stresses such as salt might have the potential to be more invasive than current crops.

6.2.8 Where there is important scientific uncertainty, what is the way forward?

Understanding the stages of plants’ life history which makes them invasive. Understanding which traits, when subject to GM, are likely to affect plant performance in natural habitats, when exposed to the full rigours of competition and predation.

Technological approaches

As well as introducing agronomic or quality traits, GM methods can introduce traits which stop a plant reproducing, particularly by seed. Although currently not entirely reliable, these technologies could be used in future to prevent any possibility of invasiveness, for example in turf or pasture grasses.

6.3 TOXICITY TO WILDLIFE

Could GM plants be toxic to wildlife, and what might be the impacts?

6.3.1 Summary

There is little scientific dispute about the fact that a GM plant engineered to produce a toxin can sometimes be toxic to non-target wildlife, since toxins are rarely species-specific. Conventional breeding techniques can also lead to unintended effects on non-target species, although the nature and specificity of these effects will depend on the mode of action and levels of expression of the transgenic or endogenous toxin.

On the other hand, finding out whether commercially grown transgenic crops many have ecologically significant impacts is more complex. It does not necessarily follow that toxicity demonstrated in the laboratory will translate into an ecological impact in the field. Currently, little information is available on the ecological impacts of GM crops on non-target species obtained from experimental field research under realistic commercial release conditions.

Conventional crop management practices, including pesticide applications, already have significant adverse impacts on biodiversity and soil functioning and the impacts of GM crops need to be assessed in this context.

No significant adverse effects on non-target wildlife resulting from toxicity of GM *Bt* plants have so far been observed in the field (with the possible exception of Event 176 *Bt* corn). This suggests that *Bt* crops are generally beneficial to in-crop biodiversity in comparison to conventional crops that receive insecticide applications. However, benefits would probably be restricted or even negated if *Bt* crops required broad spectrum insecticide applications to control secondary pests that were not sufficiently controlled by the *Bt* toxin.

The differences in soil microbial communities observed beneath GM crops have been within the range of variation in microbial community structure and of the order of magnitude of the differences observed under different crops of even different cultivars of the same crop (Dunfiled *et al*. 2001). However, almost all our information is drawn from small-scale, short-term studies and there is a need for larger, more agronomically realistic studies to be undertaken to demonstrate absence of harm to non-target organisms.

Introducing potent and/or broad spectrum toxin(s) into crop plants may create novel ecosystem dynamics, by effectively removing the crop plant as a source of food for some herbivores, detritivores and higher trophic levels. Therefore, longer-term research that compares the population dynamics of key pests and their predators and parasitoids in transgenic pest-resistant and conventional sprayed crops would be of value, although not necessarily a prerequisite for risk assessments

There is a need to develop better protocols to test the impacts of GM crops on non-target species. Future advances in knowledge of the behaviour and fate of natural or transgenic plant toxins in the environment should enable the development of predictive models that could be populated by data from field or laboratory research. Such modelling may be the best way forward for predicting environmental risks from novel GM or non-GM plants containing toxins.

6.3.2 Background

The current UK regulatory system for deliberate release of genetically modified organisms assesses a range of possible risks that could result from experimental or commercial growing of transgenic crops. One class of risk that is assessed is whether a transgenic crop may have adverse impacts on non-target organisms, (i.e. wildlife associated with the crop that does not cause economically significant levels of damage). Risk assessment for non-target toxicity applies to all GMOs, regardless of whether they have actually been engineered to contain active toxins. Since the greatest risks are likely to result from crops designed to express compounds toxic to pests, and most scientific evidence on non-target impacts of GM crops is concerned with these traits, potential toxicity of pest-resistant GM plants will be a main focus of this section. However, to date there are no commercially available applications of pest-resistant GM crops that are likely to be grown in the UK in the near future. Much of the information contained within this review may not be directly relevant to the UK at this stage of GM crop development, but there are important lessons that we can learn from experience elsewhere about techniques for risk assessment that could be useful in the future.

Although the title of this paper asks whether GM crops could be 'toxic' to wildlife, there is in fact a range of adverse impacts that both GM and non-GM crops containing altered or novel plant defences could have on non-target biodiversity. The common definition of the term 'toxicity' – the quality or condition of being poisonous, harmful, or destructive – implies a direct result of a chemical compound coming into contact with an organism. Toxicity can be 'acute' (adverse effects resulting from a single or short-term exposure to a substance) or 'chronic' (the ability of a substance to cause harmful effects over an extended period, usually upon repeated or continuous exposure sometimes lasting for the entire life of the exposed organism). Toxicity may be lethal, resulting in the premature death of an organism, or it may have various sub-lethal effects, including reduction in fertility (male) or fecundity (female), longer development time and subnormal weight, all of which could have significant effects on population dynamics of affected species. Predators or parasitoids consuming herbivorous prey that have been feeding on toxin-containing plants may inadvertently ingest the toxin(s) and suffer 'tri-trophic' effects (the plant being the first trophic level, the herbivore the second and the predator the third).

These are all examples of direct toxicity mediated by biologically active compounds. However, experimental studies have shown that the impacts of direct toxicity are often difficult to separate out from 'indirect effects' caused by changes in availability or quality of target herbivores as prey items. For example, if pest populations are strongly suppressed or even eliminated by toxin-containing plants, the predators and parasitoids that feed on those species may also decline if they lack sufficient alternative food sources. Although not strictly defined as a toxic effect of a crop, the toxicity of the crop could be said to have indirectly harmed this species (in a similar way to the non-target impacts of herbicides on the insects and birds that feed on arable plants – discussed in 6.5).

In many cases, the nature of a GM plant will indicate the obvious starting point for risk assessment. For example, a crop plant expressing a pest-resistance transgene might have novel interactions with its pest species and also with any other non-pest herbivores, or predators of crop herbivores, which are susceptible to the toxin. These kinds of interactions are sometimes predictable from previous research and theory.

Sometimes, however, the nature of new ecological interactions may be less obvious. A contribution to the GM Science Review website raises the example that some varieties of insect-resistant maize (*Zea mays*) containing a gene from the bacterium *Bacillus thuringiensis* (*Bt*) have been found to contain elevated lignin levels which cause the stalks to be broken down more slowly in soil than conventional varieties[1] (Saxena & Stotzky, 2001a). This was apparently confirmed by a study on the decomposition of *Bt* corn by the woodlouse *Porcellio scaber* (Wandeler *et al.* 2002). On the other hand, another study examined the breakdown of *Bt* and conventional lines and found increased digestibility by woodlice and found more rapid decomposition in the *Bt* lines (Escher *et al* 2000). These examples of "pleiotropic effects" might not pose significant risks to the environment, but they illustrate the importance of considering the whole plant as well as the expected effects of the transgene.

At the time of writing, the only type of insect resistance to have gained widespread marketing consent elsewhere in the world exploits a group of bacterial proteins known collectively as 'delta-endotoxins', also known as '*Bt* toxins', derived from the bacterium *Bacillus thuringiensis*. Over 100 types of delta-endotoxin have been discovered, each of which is specific to certain species of Lepidoptera or Coleoptera. The *Cry*stals of pure protein endotoxin contained by *Bacillus thuringiensis* have been used for many years in agriculture as a bacterial spray (using the whole organism), mostly on organically grown crops on which synthetic pesticides cannot be used. However, biotechnology now makes it possible to produce a single *Bt* toxin inside plant cells increasing the physical tergetting and hence the efficacy of the treatment (most sprayed *Bt* misses the plant, is washed off by the rain or does nt get nearto the target insect), eliminating the need for crop spraying. One potentially important difference between the compound produced by *B. thuringiensi*s and the toxins expressed in '*Bt* crops' is that the bacterium produces a 'protoxin' which is only converted into its toxic form once it has been ingested by an insect, whereas *Bt* plants directly express the active (truncated) toxic compound. However, evidence so far does not suggest that truncated *Bt* toxins lead to altered specificity (Evans, 2002).

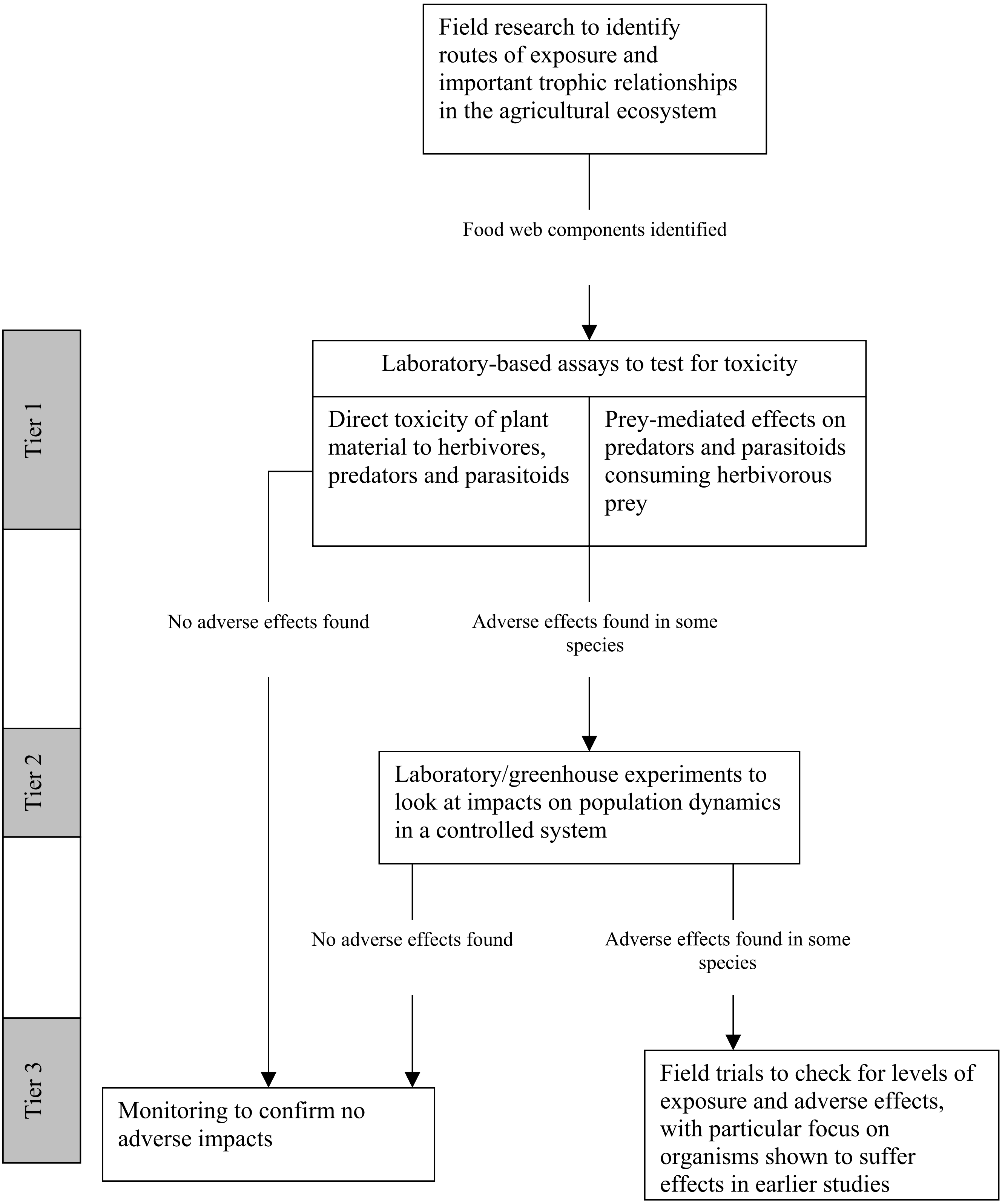
It seems unlikely that any *Bt* crops will be grown commercially in the UK within the next five to ten years. A survey of field trials conducted in the EU since 1990 revealed that *Bt* varieties of the following plants have been released: cotton, maize, rice, potato, tomato, cauliflower, broccoli, sunflower, coffee, strawberry and poplar. Of these, several are not currently suitable for commercial production in the UK (cotton, rice, sunflower, coffee) and one is a tree (poplar). *Bt* varieties of some UK crops might not be grown here for agronomic reasons. For example, although insect resistant *Bt* maize has consent for commercial cultivation in the EU, the pests it is designed to control (European corn borer or corn rootworm) are not currently a problem in the UK so there would be little incentive for farmers to grow these varieties unless they were agronomically attractive for other reasons. *Bt* tomato, cauliflower and broccoli might be possible candidates for UK growing but these still seem to be a long way from commercial development. In fact, only one field trial of a *Bt* crop (strawberries in 1995) has been carried out in this country so far. Research on the ecological implications of growing *Bt* crops is useful in terms of establishing protocols for experimental design, and perhaps for elucidating interactions between different species or guilds, but is not yet directly relevant to any forthcoming decisions on commercialisation in the UK.

In addition to *Bt*, a number of other insecticidal toxins have been experimentally introduced into crop plants, although none yet have commercial approval. They include cholesterol oxidase, vegetative insecticidal proteins, *Photorhabdus luminescens* toxins, proteinase

[1] GM Science Review Website Genewatch 2003 www.gmsciencedebate.org.uk/topics/forum/0072.htm

inhibitors, lectins and chitinases. In the UK, small-scale experimental releases have been carried out on strawberries transformed to express cowpea trypsin inhibitor and snowdrop lectin, conferring resistance to strawberry vine weevil, and potatoes expressing pea lectin, snowdrop lectin, proteinase inhibitors and pokeweed antiviral protein to confer resistance to phytophagous insect pests and potato cyst nematodes. Some of these traits may have broader pest toxicity than *Bt* and could in the future be combined with *Bt* genes to delay the development of pest resistance, a technique known as 'pyramiding' (Stewart, 1999). A number of nematicidal, fungicidal and antimicrobial compounds have also been transgenically expressed in plants (e.g. Glandorf *et al.* 1997), although many of these have been done on a purely experimental basis and none have so far been released commercially.

Diagram 6.1. Example of a three tiered risk-assessment procedure.



6.3.3 Range of views and quality of evidence

As risk is a product of hazard and exposure, both must be quantified in order to classify risks to the environment as high, medium, low or negligible. For example, the *Bt* toxin expressed in the pollen of some transgenic maize is known from laboratory studies to be toxic to some non-target species, including Monarch butterflies. These studies have identified possible hazards to non-target species, but more work needs to be done in the field to quantify exposure of arthropod larvae to the toxin, and assess the impact of toxins on population dynamics. Field studies may often be essential to quantify ecological exposure to hazards, and thus estimate risk.

But even if such risks are understood, they must still be assessed in relation to the biodiversity impacts of existing agricultural systems. In the case of *Bt* toxins in maize pollen, a valid comparison might be with current insecticide regimes used to control stem borers, the main target of *Bt* varieties of maize. Some comparative studies are already under way in the US and Europe, but are likely to be territory-specific because the relationship between biodiversity and agriculture varies between continents, countries and regions within countries, as well as with intensity of farming practices.

The discussion below has been structured in two sections to answer the question: *Could GM plants be toxic to wildlife* (hazard), *and what might be the impacts* (exposure/risk)*?*

Could GM plants be toxic to wildlife?

There is little scientific dispute about the fact that GM plants engineered to produce toxins can sometimes be toxic to non-target wildlife. Indeed, many plants have evolved chemical defences against being eaten such that they are not food sources for many herbivorous animals. However, because there is an ever-expanding range of toxins being introduced transgenically into crops, and the range of species in agroecosystems that could potentially be harmed by these toxins can vary considerably between different regions, rigorous case-by-case assessments are required to test for toxicity. A considerable amount of research has been carried out in the laboratory to test for toxicity of GM plants to non-target species. There is not yet sufficient evidence for any one crop to demonstrate absence of toxicity to non-target species. However, to put this into context, many conventionally bred crop plants, (not just those bred for pest-resistance) can also have adverse effects on non-target species, and it would be next to impossible to develop a pest control system that would have no knock-on effects past the target pest(s). More relevant issues to consider when comparing the toxicity of natural or conventionally-bred pest resistance traits (or pesticide sprays - organic or modern) with transgenically inserted traits include: novelty, specificity and dose.

Studies looking at toxicity of GM crops (or even conventional crops) to vertebrate wildlife are generally not present in the published literature. The toxins involved so far are understood only to have toxic activity on insects. However, GM crops to be used for food or feed purposes must demonstrate lack of toxicity to mammals and/or birds through feeding studies, and these are reviewed in the chapter on human health.

The fact that a GM (or non-GM) plant may exhibit toxicity to a particular organism or group of organisms does not in itself indicate a risk unless a route of exposure can be identified, i.e. that organism must come into contact with the crop or the toxin at some point during its normal life cycle. Therefore the first stage of a risk assessment should be to assess possible routes of exposure and the classes of organisms that would be exposed. Organisms could come into contact with plant-produced toxins via the aerial surfaces of the plant (leaves, flowers and stem), through its disseminated propagules (pollen, seeds and fruits), or in the soil surrounding the roots (rhizosphere). They may also contact the plant toxin directly by consuming plant material or released toxin, or indirectly by consuming other organisms that have the toxins in their gut. There may also be a temporal element to consider: plant toxins might persist in the environment for some time after the plant itself has been harvested. The section below examines evidence for toxicity of existing GM crops to some organisms that could be exposed to toxins through various routes.

Toxicity to herbivores and pollinators

Bt crops produce toxins that have a fairly narrow host range, depending on the specific *Cry* protein being expressed. The *Cry*1 and *Cry* 2 groups of toxins are specific to *Lepidoptera* (butterflies and moths) while *Cry*3 toxins are specific to *Coleoptera* (beetles). Non-target organisms likely to consume GM plant material may include species from these groups, as well as insects from other families, other invertebrates and vertebrates.

The mode of action of *Cry* toxins on target insects is well known – they bind to receptor cells in the midgut epithelium, resulting in the formation of pores which immobilise the gut, breaking up the epithelial cells and resulting in death of the organism. However, it is largely unknown what happens to *Bt* toxins in non-target herbivores and/or whether these herbivores may act as intermediaries through which the toxins may be passed on to predators and parasitoids (Groot & Dicke, 2002). It is possible that effects on predators and parasitoids may be observed due to a lower quality of their prey if they feed on/parasite species that are impacted by the *Bt* toxin(s)

In addition to the risk assessments carried out by applicants for commercial release of GM crops, there are a number of published studies that have examined the impacts of *Bt* crops on non-target organisms. Hilbeck *et al.* (2000) published a review of research on *Bt* plants and non-target organisms, which concluded that the experimental protocols used in many studies were inadequate to test for ecotoxicity, especially chronic lethal and sublethal effects. Experiments did not always adequately simulate routes of exposure that would occur in the field, and selection of test organisms was not always conducted on ecologically relevant species. However, as you cannot test every single species present in a field, non-target arthropod risk assessment has to concentrate on a limited number of indicator species. Although not always "ecologically relevant" to a given field/location, they are used because of their high sensitivity in general, making them good monitors for potential effects on other generally less sensitive species

Because of the case-by-case nature of the toxicological tests that have been carried out on *Bt* crops, it is impossible to draw any general conclusions from the research as to the toxicity of GM plants. Since *Bt* toxins can affect a range of Lepidoptera and Coleoptera, some research has focussed on the impacts on non-pest species in these families. Two studies examining the effect on Monarch butterfly larvae of consuming *Bt* maize pollen attracted a lot of attention a few years ago when they claimed to demonstrate a potential risk of growing this crop on a large scale. Losey *et al* (1999) fed Monarch larvae milkweed leaves that had been dusted with maize (corn) pollen to simulate a field situation, and found that survival of *Bt*-fed larvae was reduced by 44% in comparison to those fed on non-*Bt* pollen. Hansen and Obrycki (2000) attempted to simulate the field situation more closely by collecting milkweed leaves from the field and placing larvae on them in the lab. They found 19% mortality in *Bt*-fed larvae compared to 0% in the non-*Bt* control. These studies suggested that there could be impacts on Monarch populations in the field, but they represented a "worst-case scenario" in which larvae were given no choice of food substrate. This led to further research at the field scale (discussed in the next section) to test for impacts on Monarch populations, and none were found. A toxicological study from this research programme demonstrated that only one *Bt* variety studied (event 176) caused significant adverse effects in Monarch larvae when fed on its pollen in the laboratory, while two other events had no significant effects (Hellmich *et al.* 2001). This emphasises the need for event-specific analysis of toxicity in transgenic crops, and the need for field data as well as lab data. Further studies investigating the exposure of Monarchs to *Bt* toxin in the field and developing a full risk assessment are discussed in the following section.

Other groups of non-target herbivorous arthropods, including Coleoptera (beetles), Hemiptera (bugs), Thysanoptera (thrips) and Tetranychidae (spider mites), will ingest the toxins when feeding on *Bt* plants. Lab studies on various predatory insects have showed no non-target effects of feeding on corn pollen containing *Bt* toxin. One study examined the effect of *Bt* pollen containing the Coleopteran-specific protein *Cry*3Bb on the pink spotted ladybird, *Coleomegilla maculata*, a polyphagous predator that is responsible for suppressing pest populations in the US Midwest. No significant effects were found on a number of fitness parameters including development time, pupal weight and reproductive capacity (Lundgren & Wiedenmann, 2002). Another study found no adverse impacts of *Bt* corn pollen on *Coleomegilla maculata*, insidious flower bug *Orius insidiosus* (Heteroptera) and common green lacewing *Chrysoperla carnea* (Neuroptera), although in any case the latter is not known to feed on pollen in the field (Pilcher *et al.* 1997).

Several studies have demonstrated that aphids do not take up *Bt* toxins, since these do not seem to be expressed in the phloem, and therefore neither aphids nor the predators feeding on them are likely to be affected negatively by *Bt* plants (e.g. Raps *et al.* 2001). There is no evidence to suggest that honeybees, *Apis mellifera*, are adversely affected by *Bt* pollen (e.g. Malone & Pham-Delègue, 2001). Beekeepers often use whole *Bt* sprays to prevent wax-moth infestations of combs, apparently with no effect on the bees inhabiting the combs.

No laboratory studies looking at direct non-target effects of a non-*Bt* GM plant on herbivores or pollinators were found.

Toxicity to soil organisms

A wide range of taxa could come into contact with transgenic plant-produced toxins in the soil, including bacteria, fungi, protozoa, nematodes, springtails, mites, enchytraeid worms, millipedes, centipedes, woodlice, molluscs, earthworms and a range of soil-dwelling insects (Evans, 2002). Possible routes of exposure include direct contact with transgenic plant roots, exudation of toxins into the rhizosphere from roots and incorporation of plant debris into the soil post harvest (Saxena *et al.* 1999; 2002; Saxena and Stotzky, 2000). For example, *Cry*1Ab is present in root exudates from several varieties of *Bt* corn, but not from *Bt* cotton, oilseed rape or tobacco; *Cry*3A was found to be present in exudates from *Bt* potato (Stotzky, unpublished, reported in Evans, 2002). In certain soils *Bt* toxins can persist and retain insecticidal activity for considerable periods of time (Tapp & Stotzky, 1998; Crecchio and Stotzky, 2001). Root exudates containing *Cry*1Ab were found to have no significant effects on earthworms, nematodes, protozoa, bacteria and fungi (Saxena & Stotzky, 2001b).

A review of impacts of fungal and bacterial-resistant transgenic plants on soil microorganisms showed that research is scarce and incomplete, and mainly focussed on mycorrhizal symbiosis (Glandorf *et al.* 1997). Most studies indicate that there are no obvious effects on the saprophytic soil microflora, but these conclusions cannot be generalised. One study demonstrated that mycorrhizal symbiosis can be adversely affected, indicating that non-target effects on beneficial fungi can occur (Vierheilig *et al.* 1995). Another study of transgenic bactericidal potatoes expressing T4 lysozyme showed increased killing of the non-target bacterium *Bacillus suBtilis* on potato root hairs, although the study was insufficient to demonstrate that negative impacts would be seen on bacterial communities in the field (Ahrenholtz *et al.* 2000). Griffiths *et al* (2000) examined the impacts of a transgenic potato, producing the lectins GNA and Con A, on non-target soil organisms and processes. Laboratory studies with soil bacterial communities and a ciliate protozoan could detect no direct effect of either lectin at a range of concentrations. However, a bacterial-feeding nematode was limited in its ability to detect prey when either lectin was present in the medium.

Toxicity to predators and parasitoids

Investigating the effects of toxins on higher trophic levels (predators and parasitoids) is more complicated, since the experimental protocol needs to realistically simulate the route of exposure to the toxin. It should also be able to distinguish between different kinds of effects, no effect, and compare with current non-GM practices. These include direct toxic effects of the compound, prey-mediated effects (for example, if the prey organism alters the toxin in some way that makes it harmful to the predator), a reduction in size or nutritional value of prey due to exposure to plant toxins, and behavioural effects.

A series of tritrophic studies on the effects on green lacewing *Chrysoperla carnea* of eating *Bt*-fed prey (Hilbeck *et al.* 1998a, 1998b, 1999) demonstrated potential harmful effects on an important natural enemy. Mean total immature mortality for lacewing larvae fed on *Bt*-fed European corn borer (*Ostrinia nubialis*) and Egyptian cotton leaf-worm (*Spodoptera littoralis*) was always significantly higher than the control, and this was true whether or not the prey species was adversely affected by the toxin. Analysis revealed that in addition to prey-herbivore by *Bt* interactions, prey/herbivore by plant interactions also exist. Again however, these laboratory studies provided no food choice.

Another study examined the effect of *Bt* cotton and *Bt*-cotton fed lepidopteran prey on adult survivorship of four important lepidopteran predators of cotton pests: *Orius tristicolor* (minute pirate bug), *Geocoris punctipes* (big-eyed bug), *Nabis* sp. (damsel bugs) and *Zelus renardii* (assassin bug). Adult survivorship is particularly important as these predators often migrate into cotton fields as adults. Longevity was significantly different between control and *Bt*-fed *O. tristicolor* (-28% in *Bt*) and *G. punctipes* (-27%) but not in *Nabis* sp. and *Z. renardii*. A review of previous studies on these species shows that no significant effects had been found where the predators had been fed on *Bt* leaves. This indicates a possible prey-mediated effect (Ponsard *et al.* 2002).

Schuler *et al.* (1999) studied the impacts of *Bt* oilseed rape on diamondback moth (*Plutella xylostella*) larvae and the parasitic wasp *Cotesia plutellae*. Parasitoid larvae developing inside *Bt*-fed susceptible moth larvae inevitably died within their hosts. But wasps developing inside *Bt*-fed resistant moths suffered no measurable adverse effects from the presence of the *Bt* toxin inside their hosts. In a second study, *Bt* oilseed rape was observed to have no adverse impacts on the population dynamics of the hymenopteran parasitoid *Diaeretiella rapae* or its ability to control aphids *Myzus persicae* feeding on the crop (Schuler *et al.* 2001).

Studies of the impacts of GNA snowdrop lectin on predators and parasitoids have shown mixed results. When expressed transgenically in potato leaves, GNA confers partial resistance to two potato aphids, *Myzus persicae* and *Aulacorthum solani*. When female 2-spot ladybirds *Adalia bipunctata* were fed on GNA-fed aphids, impacts were found on fecundity, hatch rate and longevity, despite the fact that the ladybirds were switched back to a non-GNA diet halfway through the experiment (Birch *et al.* 1999). Another experiment on *A. bipunctata* fed GNA-fed aphids appeared to show no acute toxicity of GNA to the predator, although there was an indirect effect of prey size on ladybird development (Down *et al.* 2000). GNA-fed aphids have a suboptimal diet and are therefore small, so *A. bipunctata* could have been suffering from starvation or higher energy expenditure in gathering a larger number of prey items.

An endogenous parasitoid of aphids, *Aphelinus abdominalis*, could also be exposed to GNA during larval development. In one study, no direct detrimental effect of GNA on parasitoid success, development, size, emergence success, progeny survival and sex ratio was observed. However, there seemed to be an indirect host-size-mediated effect on sex ratio and size of parasitoids developing in GNA-fed aphids. GNA-fed aphids were smaller and produced a larger proportion of male parasitoids than the larger, non-GNA-fed aphids. The smaller size of parasitoids emerging from small GNA-fed aphids could have knock-on impacts on fecundity, which could in turn affect parasitoid populations in the field (Couty *et al.* 2001).

These findings demonstrate that laboratory-based tritrophic level studies are useful to assess the potential impacts of insecticidal GM plants on important invertebrates and their natural enemies.

Summary of evidence for toxicity of GM crops to non-target wildlife

The evidence presented above demonstrates that many GM pest-resistant crops, including some that are already grown commercially elsewhere in the world, have been demonstrated to exhibit either lethal or sublethal toxic effects on some forms of non-target wildlife. These effects include harm to organisms in higher trophic levels that consume plant herbivores feeding on toxic plant material. However, some of these effects may have been caused by a reduction in the quality or quantity of herbivorous prey rather than as a direct effect of the toxin itself – effects that would be a natural and inevitable consequence of any pest-resistant crop whether GM or not.

The published literature does not seem to contain any references for research on the possible toxicity of GM crops that do not contain pest- or disease-resistance transgenes. The most likely explanation is that such research is carried out as a routine element of GM commercial release applications but would not be reported in the scientific literature unless significant anomalous results were found.

The fact that some GM pest-resistant crops exhibit toxicity to non-target wildlife in the laboratory should not be considered surprising or alarming. These experiments are useful to indicate the most important organisms and interactions to test in population and ecosystem-level studies, which are discussed in the following section.

What are the likely impacts?

By carrying out experiments in the laboratory, it is relatively simple to demonstrate whether a particular organism is affected by contact with transgenic toxins. On the other hand, finding out whether there may be ecologically significant impacts is more complex and is always likely to involve extensive field-based research, not only to find out whether toxicity found in the laboratory occurs in the wild, but also to measure the exposure of organisms to the toxin under a range of conditions. Population dynamics of organisms in agricultural and semi-natural ecosystems are regulated by a number of different factors, so it does not necessarily follow that toxicity demonstrated in the lab will translate into a significant adverse impact in the field.

Impacts on herbivores, pollinators, predators and parasitoids

There is currently little published and peer-reviewed scientific information available on the ecological impacts of GM crops on non-target species that has been obtained from experimental field research that reflects commercial growing conditions. Most of the research has been carried out on small-scale plots in the United States where these crops are already commercialised. Several other studies involving impacts on non-target organisms in *Bt* crops in Europe are now under way.

Three small-scale field studies carried out in the US found no significant adverse effects on a range of beneficial insects in *Bt* (*Cry*1Ab) field corn and sweetcorn in comparison to unsprayed non-transgenic varieties. Two studies looked at predatory insects on hybrid field corn. One of these was carried out in Iowa on a very small scale (plot sizes between 22 and 45 m^2 with three replications) and found no significant differences in number of predators colonising *Bt* and non-*Bt* corn (Pilcher *et al.* 1997). The second was a larger-scale study in Michigan (plot size 4000m^2 with three replications). Population densities of *Orius insidiosus* (insidious flower bug), Coccinellidae (principally *Coleomegilla maculata*) and lacewing larvae were recorded on three days in August and September, and few significant differences were found. In addition, levels of larval parasitism of European corn borer *Ostrinia nubialis* by two ichneumonid wasps were not significantly different, suggesting that parasitism in these species is density-independent (Orr & Landis, 1997). The third was a very small-scale study in Minnesota to evaluate the impacts of *Bt* sweetcorn (*Cry*1Ab) and an isogenic non-*Bt* sweetcorn on beneficial insects. Few significant differences were observed in insect numbers between *Bt* and non-*Bt* plots. Only numbers of pink spotted ladybeetle *Coleomegilla maculata* in 1999 were significantly higher in non-*Bt* than *Bt* plots (1.17 per plant on *Bt*; 1.92 on non-*Bt*). However, the plots were small (four rows wide by 9m long) in the first year; 30 rows wide and 25m long in the second year) and density of predators was low, and with only four replications variance was high. The authors themselves recommend further research with larger sample sizes and spatial scales to investigate predator population effects of *Bt* corn (Wold *et al.* 2001).

A suite of studies was carried out specifically to test whether evidence of harm to a non-target herbivorous species demonstrated in the lab translated into an impact in the field (Sears *et al.* 2001). The experimental lab research carried out on event 146 *Bt* pollen and Monarch butterfly larvae was discussed in the previous section (Losey *et al.* 1999; Hansen & Obrycki, 2000). This research was based on a worst-case scenario that would be very unlikely to occur under natural conditions, so a major research effort was mounted to test whether significant impacts on Monarch populations were occurring in commercially grown crops, involving a series of detailed assessments of both hazard and exposure.

The results demonstrated that Monarch larvae feeding on milkweed leaves in field plots of one variety of *Bt* corn (event 176) that is known to contain high levels of *Cry*1Ab in the pollen, had 60% lower survivorship and 42% lower weight gain than in control plots. However, there were no significant negative impacts in plots containing other *Bt* corn varieties. Larvae in non-*Bt* sweetcorn fields that were treated with insecticide suffered high mortality (91-100%) (Stanley-Horn *et al.* 2001). Significantly increased mortality was also observed in black swallowtail (*Papilio polyxenes*) larvae feeding on event 176 pollen, despite heavy rainfall that may have washed much of the pollen from milkweed leaves (Zangerl *et al.* 2001). Corn pollen is typically shed during a period of around 12 days, and the peak of the migratory Monarch generation and corn pollen shed were found to overlap by 15-62% depending on the region (Oberhauser *et al.* 2001). Overall, the studies show that event 176 *Bt* corn could have adverse effects on Monarch butterflies in the field, but that all other varieties studied have little or no impacts on Monarch populations. The studies did not examine Monarch population dynamics at the field scale throughout a whole season, so there is a possibility that the less toxic *Bt* varieties could still have chronic sublethal effects on Monarchs, although the overall impacts on populations would still probably be low or negligible (Sears *et al.* 2001). Other factors, including predation and agricultural activities, are likely to have a far more significant impact on Monarch population dynamics. This is an example of research that focuses on a particular species or group of species, rather than the agroecosystem as a whole. It is essential to test specific hypotheses where potential risks have been identified, but can tell us little about the overall impacts of transgenic insect-resistant crops on biodiversity compared to the impacts of the systems that they are replacing (Lövei *et al.* 2001).

Riddick *et al.* (2000) used 500m^2 paired plots on three farms in Maryland, USA over two years to compare the impacts of *Bt* potatoes (*Cry*3A) with non-*Bt* potatoes. Both treatments received insecticide applications to simulate commercial practices (including two applications of Esfenvalerate to nontransgenic crops to prevent total defoliation by Colorado potato beetle *Leptinotarsa decemlineata*). Plant-dwelling heteropteran predators and ladybirds (Coccinellidae) were monitored during both years using sweep nets, and surface-active generalist predators were captured using pitfall traps. For most taxa there was no significant difference in abundance between treatments. However, there were significantly more spiders on the ground in transgenic than in conventional treatments. In one year there were significantly higher numbers of *O. insidiosus* in transgenic fields. The authors suggest that observed differences may have resulted from a combination of a reduction in pesticide use and from the increased plant foliage associated with transgenic plants (which were damaged less than the conventional variety). There were significantly more *L. decemlineata* larvae in nontransgenic fields. The overall conclusion was that transgenic potatoes had no deleterious effect on the abundance of the plant- and ground-dwelling predators observed in this study.

Another set of field studies conducted in Oregon examined the impacts of *Bt* (*Cry*3Aa) and non-*Bt* potatoes on non-target arthropods under a range of treatments. Six treatments and six replications were used, with each plot measuring 337m^2. Visual counts and beat cloths were used to estimate the abundance of major arthropods on potato plants. The most abundant groups of generalist predators across all treatments were big-eyed bugs (*Geocoris* sp), damsel bugs (*Nabis* sp.), minute pirate bugs (*Orius* sp.) and spiders. The abundance of these predators on unsprayed *Bt* potato plants was either comparable to or significantly higher than any other treatment. The abundance of secondary pests (not controlled by *Bt*) on unsprayed *Bt* potatoes was also higher than in other treatments (Reed *et al.* 2001) although in practice these would probably be controlled by use of systemic or foliar insecticides, reducing somewhat the environmental benefits.

A contribution to the GM Science Review website shows the results from the first year of a three-year study to compare the impacts of *Bt* cotton (*Cry*1Ac) and conventional cotton with and without insecticidal sprays on natural enemies in the southern United States (www.gmsciencedebate.org.uk/topics/forum/pdf/0088.pdf). The study found no significant adverse effects on non-target arthropods in *Bt* cotton fields, and *Bt* cotton fields often had significantly higher densities of non-target arthropods than sprayed conventional fields.

Impacts on soil organisms and processes

In gener*al.* there is a surprising lack of quantitative information on the total load of *Bt* in soil beneath transgenic crops (Evans, 2002). An unpublished field study carried out on *Bt* corn in Spain, submitted as a contribution to the GM Science Review website, demonstrated adsorption of *Cry*1Ab toxin by clays and retention of insecticidal activity against the target species *Trichoplusia ni* up to a period of eight weeks after the crop was harvested[2]. Root exudation does not seem to introduce as much *Bt* toxin into the soil as the incorporation of plant debris (Evans, 2002). No research was found in the published literature to examine the ecological impacts of plant-produced *Bt* relative to microbial *Bt* and/or routine chemical insecticide applications.

Cowgill *et al.* (2002) carried out field studies of transgenic nematode-resistant potatoes expressing cysteine proteinase inhibitors to test the effects on microbial community structure, soil microarthropods and litter decomposition. In the first year, the transgenic lines had no effect on the abundance, evenness or metabolic activity of the soil metabolic community, although one transgenic line influenced the structure of the community by favouring fungal growth relative to bacterial growth, while another transgenic line suppressed fungal growth. In the second year, microbial abundance in transgenic lines was reduced by 23% relative to the control. However, these observed changes did not result in changes in the rate of leaf litter decomposition. The transgenic lines had no significant effect on the abundance of soil microarthropods or free-living nematodes.

GNA lectin-containing potato plants were found to significantly alter the physiological profile of the rhizosphere community at harvest but effects did not persist from one season to the next (Griffiths *et al.* 2000).

Donegan *et al.* (1999) studied three types of alfalfa, either alone or in conjunction with GM nitrogen fixing bacteria, to examine their effects on the soil ecosystem. The alfalfa varieties studied were parental transgenic α-amylase producing and transgenic lignin-peroxidase producing. Lignin peroxidase is an industrial enzyme, used for large-scale lignin degradation and as a bleaching agent in the biopulping process. The alfalfa plants modified to produce this enzyme had significantly lower shoot weight, and higher nitrogen and phosphorus content. These changes in turn impacted on the soil chemistry. Soil pH was increased, and the activity of the soil enzymes dehydrogenase and alkaline phosphatase decreased. The soil biota also changed: microbial metabolic fingerprints of soil cores collected around uninoculated lignin peroxidase plants were significantly different from the parental alfalfa.

[2] GM Science Review Website. Costa 2003 www.gmsciencedebate.org.uk/topics/forum/0089.htm

This would indicate the presence of different levels and compositions of bacterial species. Lignin-peroxidase producing alfalfa inoculated with GM bacteria for enhanced nitrogen fixation also had the highest levels of culturable, aerobic spore-forming bacteria and cellulose-utilizing bacteria. Spore formation is often a response to adverse environmental conditions and has been used as an indicator of environmental stress or perturbation. The authors recommend broadened evaluation of the characteristics of transgenic plants to address such possible impacts on soil biota and processes.

Summary of evidence for ecological impacts of GM crops caused by toxicity to wildlife

No significant adverse effects on non-target wildlife resulting from toxicity of GM plants have so far been observed in the field, with the possible exception of Event 176 *Bt* corn which has since been withdrawn from the market. This suggests that the *Bt* crops that are currently grown commercially are generally beneficial to in-crop biodiversity in comparison to conventional crops that receive insecticide applications. However, this research is mostly based on small-scale field studies that have looked at densities of predators and parasitoids throughout the season, and there are no detailed studies on the population dynamics of target and non-target organisms. Additionally, we can predict that benefits may be restricted or even negated in situations where *Bt* crops require insecticide applications to control target or secondary pests that are not sufficiently controlled by the *Bt* toxin. Unfortunately there is little or no experimental evidence on these impacts in the published literature, although there is some anecdotal evidence that commercially grown *Bt* crops such as cotton often require additional sprays.

Studies on the impacts of transgenic crops on soil processes have shown some differences in soil microbial community structure, but so far there does not seem to be any convincing evidence to show that this could adversely affect soil health in the long term. This is because any potential for impact on soil ecology by GM plants must be seen in the context of natural soil variability and the currently accepted management practices that can have dramatic effects on soil microbial diversity and functions (ACRE, 2003).

Introducing potent and/or broad spectrum toxin(s) into crop plants may create novel ecosystem dynamics, by effectively removing the crop plant as a source of food for some herbivores, detritivores and higher trophic levels. Therefore, longer-term research that compares the population dynamics of key pests and their predators and parasitoids in transgenic pest-resistant and conventional sprayed crops will be very important from a basic-knowledge point of view, but is not a prerequisite or constitute an integral part of risk assessment (Hilbeck, 2002; Obrycki *et al.* 2001). For many species, GM pest-resistant crops are likely to provide significant benefits over conventional systems, but no direct comparisons have been made with alternative crop management practices such as organic farming or integrated pest management (IPM). If we want GM pest-resistant plants to contribute to ‘sustainable’ agricultural systems, their impacts on food webs and ecosystem dynamics must be understood and translated into integrated pest management practices that can be carried out by farmers.

6.3.4 Is there general scientific agreement?

A recent report from the International Council for Science (ICSU 2003) concludes that there is broad scientific agreement on a need for science-based environmental impact assessments and that the framework for such assessments is likely to be similar worldwide. Unlike in the area of food safety, there are no internationally agreed guidelines and standards for environmental assessments, so the interpretation of data and bases for comparison are subject to debate. It is this lack of agreed protocols for assessing hazards and exposure posed by GM pest resistant crops that has led to disagreements within the scientific community about the impacts of toxicity on wildlife.

An example of this is that the quality of some of the evidence used to determine applications for commercial release of *Bt* crops has been brought into question (Hilbeck *et al.* 2000). The main criticisms have been that the research does not always use ecologically relevant species and methods of exposure, and has only tested for acute toxicity rather than for chronic lethal and sub-lethal impacts.

In some cases, especially where regulators need to assess exposure of non-target organisms to a toxin within the crop, field scale trials should be essential components of environmental risk assessments of some pest-resistant plants. There may also be a need for field trials to assess the impacts of endotoxins relative to conventional insecticide use. Until recently these have not been required by regulatory systems, but requirements set out in the new EU Directive may lead to more comparative studies of this type.

There is a view among some scientists that the current generation of GM pest-resistant crops may have impacts on invertebrate community dynamics because they are designed to express high levels of a potent toxin throughout all plant tissues and throughout the season. The ecological impacts of this are expected to be different to the impacts of pesticide sprays and may be less, but we do not yet understand them sufficiently to be able to make predictions about the long-term implications for agroecosystems. There tends to be scientific disagreement about the amount of information that would be needed to demonstrate that growing GM pest and disease-resistant crops is sustainable in the long term. Some scientists would argue that reductions in pesticide use and increases in biodiversity compared to conventional crops are sufficient evidence to demonstrate absence of adverse impacts, while others advocate the need for a greater fundamental understanding of the underlying processes.

6.3.5 Is the issue unique to GM?

All plants have effective defences against herbivores, pathogens and parasites, which explains why most plants can only be attacked by a limited range of organisms. Defence mechanisms may be physically toxic to other organisms, or they may merely repel attacking organisms, by acting as physical barriers (e.g. extra lignin, waxes or hairs on leaves or stems), by inhibiting digestion (e.g. tannins) or reproduction (e.g. oestrogen mimics), or by being of suboptimal nutritional value. Considerable variation in these factors can exist within a plant species, and there is evidence that differences in host plant quality have the potential to affect long-term herbivore dynamics.

Conventionally bred pest-resistant crops can exhibit toxicity to beneficial organisms (Groot & Dicke, 2002). This can create dilemmas for plant breeders and practitioners of IPM. For example, tomato plants bred for a high expression of the alkaloid α-tomatine were found to be toxic to a parasitic wasp, *Hyposoter exiguae*, in one of its larval hosts, a major agricultural pest *Heliothis zea* (Campbell & Duffy, 1979). This resulted in prolonged larval period, reduced pupal eclosion, smaller size and shortened adult longevity, which could potentially make this for of pest resistance incompatible with biological control programmes.

However, GM does have the potential to develop plants that express novel toxins (i.e. those not found in the crop and ancestor gene pool), including some of bacterial origin. First generation GM crops were almost always developed using constitutive plant promoters, which express the toxin throughout the plant tissues and throughout the season. The absence of endogenous mechanisms for fine-tuning of the expression of pest-resistance toxins makes these early GM plants rather blunt tools for pest management. However, the discovery of new promoters that can control timing and tissue specificity of transgene expression offers opportunities for fine tuning the delivery to minimise the threat of resistance development and potential for non-target effects.

The process of genetic modification theoretically has the potential to create unanticipated alterations in the levels or nature of toxic plant metabolites, for example by inserted transgenes disrupting metabolic processes in the plant. Such 'pleiotropic' effects could be caused either through the action of the transgene product, or through the transgene being inserted into a location that interferes with the transcription of another gene(s) (see Chapter 4). Assessment of toxicity is therefore carried out on all new transgenic plants, whether or not they were deliberately designed to contain toxins. However, conventional or mutational breeding can also result in unanticipated altered toxicity, and it could be argued that all new plant varieties should be tested for such effects.

6.3.6 Are there important gaps in out knowledge or scientific uncertainties, and are these important?

It is still largely unknown what happens to *Bt* toxins in non-target herbivores and/or whether these herbivores may act as intermediaries through which the toxins may be passed on to predators and parasitoids.

Agronomically realistic ecological studies comparing the impacts on biodiversity of the use of GM pest resistant crops with conventional insecticidal crop treatments should be undertaken for any GM pest-resistant crops that are being considered for commercial release in the EU. This research will be needed in future if lectins, protease inhibitors and other endotoxins are introduced into commercial crops especially for industrial end-use.

Studies of the impacts on vertebrates (especially birds known to eat crops) of commonly used GM-derived endotoxins are lacking in the scientific literature.

There is a need to develop better protocols for testing the impacts of GM crops on non-target species. Several authors have put forward their ideas (e.g. Lövei *et al.* 2001; Hilbeck *et al.* 2002; Hilbeck *et al.* 2000; Obrycki *et al.* 2001; Groot & Dicke, 2002).

The development of models able to predict the fate of plant endotoxins within natural and agricultural ecosystems would greatly increase the ability to be able to assess environmental risk.

More field research on the impacts of pest- and disease-resistant GM crops on soil microorganisms and processes should be carried out in advance of commercialisation.

6.3.7 Likely future developments

Because the EU regulatory system now requires more detailed information on the environmental impacts of GM crops and the way in which they are cultivated, field research may be a requirement of some new applications to commercialise GM pest resistant crops. Whether such research is needed prior to an application to release a GMO or is a requirement of post-marketing monitoring is for the regulatory system to decide. Some field scale research is likely to need large scale planting of crops and might only be possible after commercial release (as part of a post-market monitoring programme).

Small-scale field trials of GM crops to test for impacts on agroecosystems are unlikely to pose any long-term risks to the environment. Most of the possible negative impacts on biodiversity resulting from toxicity of the crop are likely to be reversible, e.g. by removing that crop from cultivation should any harmful impacts be observed.

However, there are some potential impacts of growing GM crops, either in field trials or more likely through commercial cultivation over several years, which could be irreversible. For example, gene flow from a pest-resistant crop to wild relatives that led to an increase in fitness could result in that plant increasing in density and/or expanding its range (see section 7.3). This could lead to the decline of less competitive plant species and/or declines in organisms in the food chain of those plants that were adversely affected by the toxin. Another potential irreversible impact could be the development of resistant pest populations through intense selection pressure, as happens now in non-GM agriculture. Therefore, it will be important to consider these risks (discussed in section 6.4) when deciding whether to proceed with field trials and/or commercial cultivation.

6.3.8 Where there is important scientific uncertainty, what is the way forward?

For the commercial cultivation of GM crops in the EU there is a legal obligation to include a post-market monitoring programme, aimed at testing the validity of assumptions made during risk assessment, identifying any unforeseen adverse effects on the environment or human health. Since our understanding of the impacts of GM crops on non-target species will never be complete, in cases where the environmental risks are assessed to be acceptably low, regulators are likely to grant commercial consent with the option of withdrawing consent if monitoring programmes identify significantly harmful impacts. Such monitoring programmes can be used to add to knowledge of the impacts of GM pest-resistant plants on the general environment.

Future advances in knowledge of the behaviour and fate of plant toxins in the environment should enable the development of predictive models that could be parametized by data from field or laboratory research. Such modelling may be the best way forward from predicting environmental risks from GM plants containing toxins.

6.4 DEVELOPMENT OF RESISTANCE

Could crops engineered with novel resistance genes lead to the emergence of new forms of pests, diseases and weeds that are resistant to chemical sprays? Will new forms of insects and diseases evolve which are able to bypass GM resistance genes?

Herbivorous insects, fungal pathogens, bacteria and viruses often get around disease resistance genes by mutating to new virulent forms. Is this more likely to happen with a GM-derived resistance gene than with a conventional bred resistance gene, and will the impacts be greater? Similarly weeds can develop tolerance to herbicide sprays. Is this likely to be a greater problem when herbicides are used with GM HT or other HT varieties?

6.4.1 Summary

Two key plant breeding aims, both of GM and other breeding technologies, are the development of varieties that are resistant to pests and diseases, and crops which are tolerant to herbicides. Disease resistant varieties, particularly if grown on large areas, provide a strong selection for *target organisms* (pests or pathogens) that can attack the new variety. Similarly new forms of pests, diseases and weeds can develop that are tolerant to any agro-chemicals applied to reduce incidence of disease or to kill weeds.

The time it takes for a virulent or resistant pest or pathogen to emerge depends on the nature and complexity of the genetic mechanism that makes the crop toxic to the pest immune to the disease and on the effectiveness of the management techniques deployed by the farmer. Current opinion is that ‘single gene’ mechanisms are less durable than immunity controlled by several genes. That said, some ‘single gene’ sources of resistance (GM or non-GM), including the *Bt* genes which confer resistance to insects, appear particularly robust and have not yet broken down in the field. However, all experience and science tells us that any gene-based resistance mechanism will eventually be overcome.

Similarly, weeds resistant to herbicides have been seen for various herbicides applied in association with herbicide-tolerant crops. This is the case whether the tolerance was introduced by GM or any other breeding technique. Weeds that are closely related and can hybridise freely with a herbicide-tolerant crop variety have the additional possibility of obtaining tolerance directly from the crop.

The conclusion is that, although new forms of plant pests, disease and weeds can be expected to emerge, there is no evidence to propose different responses depending on whether the resistance was introduced into the crop by GM or other breeding methods. The use of a diversity and/or combination of strategies for weed/pest control would expect to delay or even prevent resistance evolving.

6.4.2 Background

The evolution of virulence in plant pests and diseases allowing them to overcome resistant varieties of crops is a major concern for breeders; for example the insect targeted *Bt* crops or rice bacterial leaf blight targeted by the *Xa21* gene. Similarly, the emergence of new varieties of weeds resistant to herbicides used on herbicide tolerant (HT) crops is a concern. This has been highlighted in the Review of Public Concerns with the question 'is it speeding up a natural process like survival of the fittest?' The issue of the emergence of herbicide tolerance in weeds has been addressed in a website contribution[1].

The development of resistance is not a novel phenomenon confined to agriculture, and certainly not to GM. The reciprocal selection pressures between a host and a parasite (termed co-evolution) are thought to be very important. The Red Queen hypothesis (Van Valen, 1973), derives its name from the character in 'Alice Through the Looking Glass', who tells Alice, "It takes all the running you can do, to keep in the same place", proposes that sexual reproduction persists because it enables species rapidly to evolve new genetic defences against parasites that attempt to live off them. Chromosome recombination and reassortment during sexual reproduction increases genetic variability in the population, which increases the chances of survival chances of some individuals in times of altered selection pressure. This is the basis of adaptation. It was Haldane that first argued that disease was one of the most important evolutionary agents, and its importance increases in line with its killing power.

These notions extend to the agricultural environment where chemical agents to control disease, pests and weeds are used extensively in modern intensive farming practices. Pesticides and herbicides are often effective for only a short time, until new cycles of co-evolution produce new forms of the target pest, weed or pathogen that can tolerate the chemical. A similar situation pertains with crop genetic resistance to pests and diseases, which, although usually more targeted to a specific crop organism, also exerts selection pressure that can results in new, more virulent forms of the pest or pathogen. This has been highlighted in the Review of Public Concerns with the question 'could harm take the form of new diseases? (D5- see Annex 1)'

This paper addresses issues associated with:

(a) The likelihood and speed of breakdown of GM resistance to pests or diseases, and of weeds evolving resistance to broad-spectrum herbicides used on GM HT crops, and the effectiveness of management strategies that can be used to reduce the speed at which resistance may evolve.

(b) The potential impact of resistance breakdown, and the development of herbicide tolerance in weeds.

(c) Whether we can expect differences between responses to resistance genes and herbicide tolerance genes incorporated in new varieties by GM or other breeding methods.

An understanding of the molecular and genetic basis for resistance is crucial in modelling the probability of parasites deriving resistance. Resistance may be determined by a single gene or controlled by many. See Box 6.2

It is important to note that although insect pests may reduce crop yields, associated and often more serious effects are caused by viruses that are transmitted by the insect, or by fungal or bacterial diseases that enter the plant through the insect puncture holes.

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[1] GM Science Review Website. Hartzler 2003 http://www.gmsciencedebate.org.uk/topics/forum/0051.htm

Pest and disease resistance mechanisms in plants are of two types: 'gene-for-gene' specific resistance that we expect will be overcome by mutation and selection in the pathogen population and 'durable' (non-host) resistance that we expect to be more robust (see Box 6.2).

The probability of resistance breakdown arising will depend on the frequency of resistance alleles in the population, the method of inheritance (controlled by a single or multiple alleles which are dominant or recessive), the level of the selection pressure and, in insects, the mating ranges of the pests. In addition, resistance management strategies that aim to make the conditions as difficult as possible for the target organism to evolve resistance are often employed.

Box 6.2. Pathogen Type and Genetic Basis for the Evolution of Resistance

Genetic Basis for Resistance between host and pathogens

Gene for Gene – Race-specific resistance, conditioned single genes, is the best understood form of constitutive plant disease resistance and has been widely used in breeding. Each resistance gene in the host has a matching gene for virulence in the pathogen. It takes only one mutation in the pathogen's avirulence gene to create a protein that is not recognised by the host thereby laying it open to attack. This sometimes referred to as 'resistance breakdown'. It is important to note that resistance and avirulence genes tend to be dominant. Plant breeders have in the past concentrated on this sort of major gene resistance that is easier to select for. This has given rise to 'boom and bust' cycles (e.g. yellow rust in the UK wheats in 1970s).

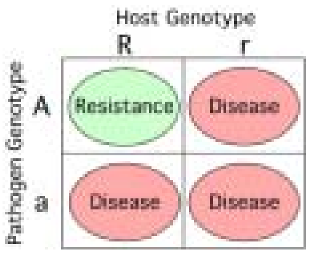

Fig. 1 Schematic representation of race specific, 'gene-for-gene' resistance

Durable Resistance – Resistance which is controlled by several genes is harder to circumvent because a mutation in any one of them is unlikely to confer resistance on its own. Durable resistance is generally broad spectrum as it does not rely on the host recognising the pathogen. This is less well understood than race-specific resistance, but is an important goal of plant breeding.

Types of Pathogens

Biotrophs – specialist interaction with hosts , generally obligate. Many fungal diseases fall into this group (rusts, mildews), but also some bacterial diseases. They generally have major 'gene-for-gene' resistance genes, but also have other, non-specific resistances that are generally durable.

Hemi-biotrophs – initially grow on plant without symptoms, then evidence of disease becomes apparent, e.g. *Septoria.*

Necrotrophs- non-obligate, saprotrophic stage, greater influence, have a role away from the host, generally not 'gene-for-gene' and thought to be polygenic.

6.4.3 Range of views and quality of evidence

The likelihood and speed of breakdown of GM resistance to pests and diseases, and of weeds evolving resistance to broad-spectrum herbicides used on GM HT crops, and the effectiveness of management strategies that can be used to reduce the speed at which resistance may evolve.

The probability of a pathogen overcoming resistance in a GM or non-GM transgenic crop and the crop management strategy deployed is very case-specific.

Evolution of resistance to herbicides in weeds is also expected. HT is sometimes discovered in weeds and wild crop relatives that have never been exposed to the chemical. There are many reports of HT arising in response to herbicide sprays and, more recently, in responses to sprays on both GM and non-GM HT crops. In the last 40 years more than 120 plant species worldwide have developed herbicide resistant individuals under modern agricultural conditions (see section 7.3.3).

Pathogens

There are now several examples of transgenic resistance to bacterial and viral pathogens that cause disease. Only a few will be discussed below. Note that, in addition to natural mutation in pathogen populations as a basis for breakdown of a resistance gene, importation of more virulent strains of pathogens from elsewhere are often the cause of breakdown.

Bacterial disease

Xa21 is a gene discovered in *Oryza longistaminata*, a wild relative of cultivated rice. It was introduced into rice by crossbreeding and found to be effective against all known races of bacterial leaf blight (*Xanthomonas oryzae*), in rice (Khush 1990). It was subsequently isolated (Song *et al.* 1995) and made freely available to public breeding programmes in developing countries.

The gene can now be manipulated in cross-breeding programmes and pyramided with other resistance genes (Huang *et al*. 1997) or used directly as a transgene. The gene has held up so far, either in transgenic or conventionally bred lines, and so may be durable.

Viral disease.

Viruses often have a devastating effect on crops and much agro-chemical pest control is directed at the insects, fungi, mites or nematodes that naturally transmit these viruses. The introduction of durable genetic resistance against many common, and often devastating plant viruses is seen as a more sustainable means of crop protection than frequent spraying with chemicals to control the pests that transmit them.

Virus resistance gene breakdown is commonplace, e.g. Tm1 and Tm2 *genes* overcome by Tobacco Mosaic Virus and the emergence of new strains potato virus X (PVX) in Latin America which overcame the natural *Rx* genes. Although PVX has been fully investigated most other examples remain empirical observation without full understanding of the molecular mechanisms involved.

Over seven years, several GM food crops expressing virus-derived sequences as novel resistance transgenes have been deployed commercially in the USA, China and Africa there has been no reported case of any new strain of a virus "breaking" the GM resistance. Box 7.1 lists some seven successful applications of GM to give resistance to viral infection in papaya, wheat, rice, potato, chilli pepper and tomato. Perhaps this is because most viral R-genes function through a highly targeted and efficient plant defence/RNA degradation pathway related to RNAi-mediated gene silencing which inhibits the earliest stages of virus replication before large numbers of viral genomes accumulate to recombine or be mutated. Nevertheless, long history and experience tell us that, sooner or later, any single dominant virus-derived R-genes will be overcome by a new strain of the target virus.

Management and breeding strategies

There are several management strategies to delay resistance breakdown. These include the use of seed 'mixtures', different varieties carrying a range of resistance genes all mixed together (Wolfe and Barrett 1980, Mundt 2002). This is expected to reduce selection pressure on the pathogen within a field. On a larger scale, the deployment of a range of varieties with different resistance genotypes on a farm or within an agricultural area has been proposed (Priestley & Bayles 1982). Others however claim fungal spores are dispersed over such long distances as to make fields ineffective as barriers (Brown and Hovmøller 2002).

Pests

Insect pests are not a major problem in UK agriculture, however, elsewhere various insects are major pests themselves and, in addition, many transmit virus diseases. Natural insect resistance, for example to rice plant hoppers and gall midge, has been a major target in breeding programmes the world over. Effective alleles have been found in germplasm collections and in wild relatives of crops. Although the toxins involved in most of the resistances are unknown, gene-for-gene relationships are common as is resistance breakdown. Investigation of *Bacillus thuringiensis*, used as a sprayed insecticide led to the discovery of the *Cry* genes that underpin the transgenic *Bt* crops. The main differences between *Bt* transgenic crops and *Bt* sprays is the GM plant will express the toxin at a high dose throughout the growing season, which may decline at the end of the growing season making it easier for resistance to evolve. Sprays also involve a large numbers of toxins, whereas GM varieties use the products of only one, or more recently, two genes.

There are several strains of *Bt* which produce a range of *Cry* proteins and target a spectrum of insects, mainly lepidoptera, such as the European corn borer and boll worm, most of which are not pests in the UK. Therefore, *Bt* transgenic crops are unlikely to find application in the UK in the foreseeable future, it is useful to draw on the growing this experience of this group of transgenic crops.

As yet there has been no confirmed reports of breakdown of resistance in the field in the many crops that have been engineered with *Bt* genes, some of which have been planted since 1996. However, there is no reason to suspect that *Bt* will not break down. In fact break a decrease in sensitivity to certain *Bt* toxins by certain strains of target pests has been observed under laboratory conditions. In order to further delay breakdown, breeders are incorporating more than one gene at a time into new varieties, e.g. the two *Cry* genes now engineered into Australian Inguard cotton varieties (Peacock 2003).

In Australia, there are opinions that the addition of a second *Bt* gene will alter the balance of insect pests with increases in insects such as aphids green mirids and two-spotted mites which will demand more complex control measures (Fitt, 2001).

This is contested by Peacock, who insists no effects on 200 species of non-target insects have been observed in several years of monitoring (Peacock 2003). Also elsewhere diet feeding experiments indicate that the effects of the Cry1(c) protein on non-target insects are negligible (Sims, 1995)

Management strategies

The management of pest resistance currently favoured is the 'high dose/ refuge' strategy, in which farmers are required to leave small areas within the *Bt* area planted to susceptible varieties (Tabashnik, 1994; Huang *et al.* 1999). This strategy reduces the risk of resistant individuals surviving to mate (due to the high doses) and reduces the risk of doubly recessive individuals surviving to mate (creating a low percentage of these due to the compulsory use of refugia). See box 6.3. Whether or not the use of refugia is an effective strategy cannot be established until we have experience of resistance breakdown. The effectiveness of refugia has been questioned as has the possibility of applying the strategy on the smaller *Bt* cotton farms in, for example, South Africa, China and India (Jayaraman, 2002). Other critics of "high-dose/refuge" strategy argue that some of the assumptions to not hold for the European corn borer [2]. However *Bt* has been in the field now for many years so it may be durable.

Box 6.3 The principles of and assumptions underlying refugia

REFUGIA

Refugia are areas where susceptible insects may live, i.e. a 'refuge' from the insecticidal plants. It may consist of an area of non-insect resistant plants grown in the vicinity of the insect resistant crop, or dispersed amongst them. The aim of refugia is to keep a susceptible population for mating with resistant individuals, thus reducing the number of resistant alleles in the insect population.

The concept of a refuge relies on several three key factors: (a) resistance alleles are rare, (b) resistance alleles are recessive, (c) insects growing on the crop and the refuge come together to mate, and (d) crops contain high concentrations of the toxin in certain tissues.

Refuge requirements are designed on a case-by-case basis, considering the biology of the target pests and the nature of the cropping system. Examples of current refuge requirements for *Bt* corn are:

1) in the USA – in the "corn belt", growers must plant a 20% refuge area, which must be planted within one-half mile of the biotech field, and must contain non-Bt corn.
2) in Argentina – farmers are required to plant a 10% non-Bt corn refuge. This is smaller than the US because alternative host crops for the target pests serve to supplement the structured refuge. (Source, Monsanto contribution website)

Because of the conditions necessary for Refugia to be an efficient resistance management technique, it is only applicable to insect pests where mating partners grow on separate plants. It is important to ensure that insects from the main crop and refugia mate together and do not develop asynchrony, which has been documented in a few cases (Lin *et al.* 1999, Cerda and Wright, 2002)

Concern is sometimes expressed that GM makes it possible to introduce similar pest resistance genes into different crops (e.g. Bt for insect resistance) and that this therefore has a greater potential to select pests that overcome the resistance. However, different crops generally have a different spectrum of pests and diseases and therefore will usually require

[2] GM Science Review Website. Castanera 2003 http://www.gmsciencedebate.org.uk/topics/forum/0090.htm

different resistance genes to control them (e.g. different Bt genes or other resistance genes, or non-host resistance where a pathogen has no potential to infect a particular species).

Weeds

Genetically engineered crops resistant to a herbicide introduce the opportunity for routine use of broad-spectrum herbicide for weed control. Past case history in chemical weed control suggests that recurrent selection will frequently result in the emergence of resistant weed phenotypes. A range of herbicide tolerances have now been built into crop plants. Conventionally bred HT (atrazine) maize varieties were deployed in the US in the late 1980s. Roundup Ready (glyphosate tolerant) varieties of many crops, including maize, soybean, oilseed rape and cotton, have been bred by GM using two bacterial gene sequences. Increasingly non-GM sources of HT are being used, these include triazine and imidazolinone tolerance in oilseed rape and chlorsulfurun tolerance in wheat (Mazur and Falco, 1989). Tolerance to glyphosate is proving difficult to find or induce by mutation in crops. Nevertheless resistance in weeds is common and a defined spontaneous mutation for glyphosate resistance has been described in *Eleusine indica*, a wild weedy relative of finger millet (Ng *et al.* 2003).

The development of resistance to herbicide sprays is common. In some cases resistance can be found in crops, e.g. ryegrass and *Sestuca* (Johnston *et al.* 1989), emmer wheat (Snape *et al.*1987) and *Setaria viridis* (Wang *et al.* 1998), on which the chemical has probably never been applied. The first herbicide resistance weeds (to triazines) were reported in 1968. Since then, herbicide resistance has been observed worldwide and has been shown in at least 127 species covering 15 herbicide groups (Mortimer and Putwain, 1991). Characteristically, evolution to triazines in most species emerged after prolonged (typically 7-10 years) exposure to the herbicide. Highly resistant plants to chlorosulfuron occurred after three years in which the chemical was applied at 7-14 month intervals (Thill *et al. 1991*).

Emergence of glyphosate (Roundup) tolerance following repeated treatment has now been documented for a range of weeds, starting with ryegrass in Australia and now worldwide with a range of species[1]. In Canada volunteer oilseed rape with multiple tolerances to glyphosate, glufosinate and imidazolines (Liberty, Roundup and Clearfield - three of the herbicide tolerances used in Canadian canola varieties) has been found. They were first identified in Canada in 1998, only three years after GM HT oilseed rape was first grown (Downey, 1999). This resistance has presumably arisen from sequential crossing of several herbicide tolerant varieties and subsequent 'gene stacking' of an imported trait and not due to mutation. Although glyphosate has been used for more than 28 years, there have been a maximum of 4 reported cases of weeds developing resistance due to repeated exposure (mutation or other unknown mechanism of resistance). In theory, tolerance in some other weeds could also be derived through hybridisation with a HT related crop plant. No example of this sort of gene transfer has yet been observed.

The multiplicity of herbicides available ensures that HT gene-stacked volunteers are not an agricultural problem. Both 2,4D and paraquat (grammoxone) are being recommended by government agencies to control herbicide tolerant oilseed rape volunteers in Canada (Orson, 2002). However English Nature considered that if herbicide tolerance gene stacking arose in the UK, more paraquat and diquat use could result in harm to hares.

Management techniques

Management practices to avoid resistance could harm or benefit biodiversity (Orson, 2002). Theory suggests that for monogenetically inherited resistance, alteration of selection intensity by rotation of herbicides with different modes of action or the use of non-selective cultural methods will be effective in delaying the emergence of resistance. These management techniques (e.g. crop and herbicide rotation) are often implemented by farmers, but there is no regulation.

The potential impact of resistance breakdown, and the development of herbicide tolerance in weeds.

Disease resistance breakdown has been a common unfortunate event in varieties of, probably, all bred crops. In many cases alternative natural genes and alleles are available to the breeder to incorporate into the next wave of resistant varieties, which will already be in development. The major impact is economic, both at the level of the farmer who has lost yield and profit, and at the level of breeder with the costs involved in breeding effective alternative varieties. The economic impact of breakdown in transgenic crops is likely to be greater still because of the high costs involved with satisfying the present regulatory processes. There may also be environmental impacts where farmers resort to fungicidal sprays when genetic resistance becomes ineffective.

Pests

There will be similar costs associated with adaptation of pests to insect resistant varieties as for plant disease resistance breakdown. The breeding consequences might be more severe because effective alternatives to the Cry genes are probably not available.

The most likely immediate consequence will be that farmers will return to the previous insecticidal spray regimes with the associated economic costs (Conway 2003, National Research Council 2000).

HT weeds

Should target weeds become resistant to any single or several herbicides the most immediate effect is again likely to be an economic one, i.e. from loss of production due to excessive weeds or from the added cost of removing the HT weeds with a second herbicide. The actual economic impact is likely to be situation specific. Hartzler[1] describes different weed scenarios in glyphosate resistant crop that would involve the farmer in more or less expense.

The environmental impact could also be significant. Resistance to herbicides that are broken down rapidly in the soil, such as glyphosate, would mean that they would likely have to be replaced by herbicides such as 2-4D or diquat that can persist in soils for long periods. This increase in paraquat and diquat use could result in harm to hare populations in the UK (see above).

Whether we can expect differences between responses to resistance genes and herbicide tolerance genes incorporated in new varieties by GM or other breeding methods

There is no evidence, or reason to expect, that breakdown to GM-derived or conventionally bred resistance will result in different forms of disease to breakdown of natural genes. The incorporation of, for example, *Xa21* into rice, by GM is unlikely to result in different consequences to its incorporation by GM. The use of such natural plant genes in transgenic programmes is likely to increase.

Herbicide resistance is developed to the herbicide, whether it is sprayed in association with a HT crop or not. GM HT crops could increase areas being sprayed with a particular herbicide (as in the US) and increase the frequency of the application. This could increase the likelihood of resistance developing[1].

6.4.4 Is there general scientific agreement?

There is agreement that resistance genes, introduced by GM or otherwise, are likely to be overcome by the evolution of resistance, especially where control relies on just a single gene.

There is debate as to whether the rates of co-evolution in response to, for example *Bt* genes, is likely to be more rapid than to resistances against other pathogens, such as viruses, or resistance to sprays including *Bt*[3].

There is considerable debate over the effectiveness of agricultural management methods to slow down breakdown, particularly for *Bt*. These arguments are unlikely to be resolved until actual breakdown occurs. There are also differences in opinion about the likely severity of impacts on agronomy and biodiversity where resistance develops, i.e. will resistance to glyphosate be a problem and whether it can be managed.

6.4.5 Is the issue unique to GM?

Not in the sense that disease and pest resistance genes have been bred into crops by both GM and other breeding methods. Similarly herbicide tolerance has been bred in several ways. In fact, non-GM HT is likely to become more common while the difficulties in progressing new GM varieties through the regulatory process persist. Resistance breakdown and HT development is expected to be similar in principle in either case. However, GM's ability to incorporate a toxin throughout the plant means potentially greater exposure and thus greater selection pressure, which is why for Bt the concept of refugia has been developed.

6.4.6 Are there important gaps in out knowledge or scientific uncertainties, and are these important?

- The nature of the toxins underlying the action of 'natural' insect resistance genes.
- The nature and mechanism of 'durable' (non gene-for-gene) resistance.
- Whether non-host resistance can be used as sources of durable resistance.
- The effectiveness of the refugia strategy.
- The relationships between 'fitness' and response to resistance genes.
- The ability to understand and predict weeds shifts associated with the widespread use of broad-spectrum herbicides over growing crops.

[3] Open Meeting. Hails 2003, http://www.gmsciencedebate.org.uk/meetings/pdf/170303-speaker-2.pdf

6.4.7 Likely future developments

Today more than twenty plant disease resistance genes have been isolated. Many of these share just a few similar functional domains, and the predicted products can be classified into just five groups - detoxifying enzymes, kinases, nucleotide binding sites/leucine-rich repeat and receptor kinases.

Swapping resistance genes from one species to another

As more native plant disease resistance genes become isolated it will become possible to transfer these between species. Successful reciprocal transfers of virus resistance gene between tobacco and tomato (Whitman *et al.* 1996, Thilmony *et al.* 1995, Rommens *et al.* 1995) indicate that signal transduction pathways are conserved and that further transfers may be effective.

Designer genes

It may soon be possible to design new disease resistance genes in the laboratory. Several groups are using the comonalties in functional domains of different genes to design genes with novel specificities by mixing and matching domains from diverse resistance genes. Similarly there are indications that transgenic plants with hairpin constructs of segments several topovirus N-genes can confer broad spectrum resistance to a range of topovirus[4] which may open up yet more designer opportunities

Gene pyramiding

The assembly of multiple resistance genes, both GM and non-GM, in single varieties may make resistance more durable but would probably make impacts on non-target organisms (and impacts on fitness of wild relatives via gene flow) harder to predict.

Reducing gene flow

Expression of resistance genes or herbicide tolerance genes in chloroplast rather than nuclear genomes[5] could eliminate the likelihood of gene flow via pollen.

6.4.8 Where there is important scientific uncertainty, what is the way forward?

Resolution of the areas of uncertainty outlined above will aid the development and effective deployment of improved and more predictably durable disease resistance for crops. Time and more targeted and co-ordinated research are necessary.

[4] http://www.embo-keszthely.abc.hu/
[5] GM Science Review Website. Birch 2003, http://www.gmsciencedebate.org.uk/topics/forum/0054.htm

6.5 NEW WEED CONTROL STRATEGIES OFFERED BY GM HERBICIDE TOLERANT CROPS

Will herbicide tolerant crops offer new weed control strategies and, if so, what are the likely impacts, positive and negative?

6.5.1 Summary

The introduction of genetically modified herbicide tolerant (GM HT) crops into the UK would, for the first time, give growers the possibility of using effective broad spectrum herbicides on crops where weed control has up until now been difficult to achieve. These changes could bring with them a range of environmental impacts, positive, negative and benign.

While there may be only modest declines in overall herbicide use, it is nevertheless likely that the more environmentally benign herbicides, glyphosate and glufosinate, could come to replace some of the more damaging herbicides currently in use. Inevitably, however, this benign characteristic does not extend to their impact on target organisms (weeds).

Weed control is potentially simpler for the GM HT grower than conventional cultivation and provides more flexibility, particularly in application dates. By delaying application dates growers could, in principle, use this flexibility to deliver more biodiversity by leaving weeds in fields for longer. However, there is only limited evidence that this can be done successfully, and the longer–term impacts on biodiversity have been questionable.

Evidence from the US suggests that GM HT cropping may favour reduced tillage that can itself deliver some environmental benefits; reduced soil erosion, increased carbon sequestration and potentially increased biodiversity. However, it is unclear whether GM HT cropping in the UK would lead to a renewed interest in reduced tillage, and some of the benefits of reduced tillage could be realised without GM cropping.

There has been a substantial decline in farmland biodiversity in recent decades and it is generally accepted that these declines have been caused by agricultural intensification. There is less evidence to indicate the relative contribution of herbicides *per se* in these declines but there is sufficient knowledge, particularly from studies of birds, to suggest that should weed populations decline further, then species that are dependent upon weeds may be adversely affected.

GM HT cropping may provided more efficient weed control than conventional regimes. However, because most comparative studies have been conducted within a single season, it is unclear whether reductions in weed populations would only be limited to that season or would further exacerbate the documented long-term declines in weed populations, or lead to shifts in weed communities over time.

There have been suggestions that GM HT cropping could be beneficial for biodiversity; these remain speculative. This is because the relative importance of the potential biodiversity gain (itself uncertain) from improved weed populations early in the season, and potential losses from reduced weed seed resources late in the season (generally accepted as likely), and reduced weed populations in the long-term (not yet studied in detail), are largely unknown.

There remains real scientific uncertainty over the impacts of GM HT crops on farmland biodiversity in the UK because few studies have been completed. The publication of the results of the UK government funded farm-scale trials of GM HT crops, established to investigate the impact of the management of these crops on farmland biodiversity, will clarify some of these uncertainties, though others remain to be studied.

Herbicide tolerant crops are being bred by both GM and non-GM methods. Some recent developments in non-GM breeding mal eventually lead to crops tolerant to broad spectrum herbicides. However, in the UK, the possibility of early commercial approval of GM HT crops represents the first major potential deployment of broad spectrum HT crops. Case-specific post-market monitoring and general surveillance is now a regulatory requirement which should provide information on this point for any crops which receive commercial approval for growing in the UK.

Real concerns remain that GM HT crops may represent a further ratchetting up of the intensity of UK agriculture in ways that will further reduce our depleted farmland biodiversity. Although these concerns remain, they are very far from being proven and so this area remains one of scientific uncertainty.

6.5.2 Background

The Corr Wilbourn Foundation Discussion Workshops indicated considerable public concern about the effects of new GM crops on the environment and wildlife in the UK. Amongst others, questions such as *'Is it [GM] destroying nature as we know it?'* and *'What will be the effects on wildlife?'* indicate the types of issues about which some members of the public feel concern over GM crops.

Some regard these worries as ill informed or scare mongering, and it is certainly true that worries about wildlife are anthropocentric in nature[1] and based on value-judgements. However, these concerns are backed up by legal obligations; the UK has international obligations under the EU Habitats Directive, the EU Birds Directive and the Convention on Biological Diversity to safeguard its native biodiversity. In addition, domestic legislation (notably the Countryside and Rights of Way Act 2000, which applies to England and Wales) confers duties on government departments and agencies to have regard to biological diversity throughout the landscape and to promote the conservation of important habitats and species.

6.5.3 Range of views and quality of evidence

The introduction of genetically modified herbicide tolerant (GM HT) crops would offer growers new weed control strategies largely unavailable under conventional agricultural regimes. Crop management involves the use of a broad spectrum herbicide on a growing crop that has been genetically modified to be tolerant to it.

A range of impacts, positive, negative and benign, has been proposed for GM HT crops. The potential benefits of GM HT cropping include: more simple weed control, more flexible weed control (for example delaying herbicide applications), a reduction in the use of persistent herbicides, a reduction in mechanical tillage and weed control, and reduced insecticide use as

[1] Prof. Sam Berry: http://www.gmsciencedebate.org.uk/topics/forum/0058.htm

pests are diverted to non-crop plants (weeds). Some of these potential benefits accrue to the grower, some to the environment more broadly, some to both.

The most important potential disadvantage is that weed control in GM HT crops may be so efficient that it will further exacerbate the declines of the non-crop flora, and those organisms that depend on it [2,3]. Other potential disadvantages, such as gene-stacking are discussed elsewhere.

There are developments in the production of herbicide tolerance by non-GM breeding, in some instances conferring tolerance to broad spectrum herbicides (e.g. glyphosate). Agronomic changes associated with the commercialisation of these could have parallel impacts on the environment. The issue is therefore not specific to GM crops although, in the UK, GM HT crops represent the first.potential major deployment of HT crops and this will remain the case for several years (see Chapter 6.6).

The following sections consider the potential advantages and disadvantages of GM HT cropping in more detail, and examine the evidence to support these assertions.

A quick introduction to GM HT crops

Control of weeds in crops has been a key goal for farmers for centuries. Initially, cultivation, crop rotation and seed cleaning were the principle options. Herbicides were introduced during the 20th Century in the UK, initially to control broad leaved weeds and later for control of grass weeds (Lockhart 1989). Selective herbicides - which kill target weeds but not the crop - have been in practical use in the UK for over 50 years. This selectivity was achieved by chemistry (testing novel compounds on weeds and crops), genetics (breeding from existing crop varieties for greater resistance to herbicides) and through mutation breeding. The advent of genetic modification has allowed the development of crops that allow the use of broad spectrum herbicides which had hitherto only been used in situations where all treated plants were to be controlled (killed).

No GM HT crops are grown commercially in the UK at present, but several are the subject of small scale or farm scale trials. A variety of crops are being studied, but those that are potentially closest to commercial release are maize, oil seed rape (spring- and winter-sown) and beet (sugar and fodder). In any one year, conventional varieties of these crops in Britain occupy around 170,000 ha for sugar beet, 10,000 ha for fodder beet, more than 100,000 ha for maize (forage), and 60,000 ha for spring- and 470,000 ha for winter-sown oilseed rape (Nix 2001, HGCA 1999). However, as these crops are grown as breaks within cereal rotations, the total area of land on which these crops are grown could be at least three times greater.

Each of these crops has been made to be tolerant to a broad spectrum herbicide, most commonly either glyphosate or glufosinate ammonium. When sprayed with these herbicides, the weeds are controlled, but the crop is not harmed. The advantage of using a broad spectrum

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[2] The UK government's statutory nature conservation advisors, English Nature, the Countryside Council for Wales and Scottish Natural Heritage, have a joint position on GM crops (http://www.english-nature.org.uk/news/statement) which states that:

> *'…the use of transgenic techniques, incorporating new combinations of genes into crops and other commercially valuable organisms, may pose additional risks to our natural heritage due to potential impacts on ecological food webs. In addition, there is potential for GMOs to enable changes in agricultural, forestry and fisheries management, which could be detrimental to wildlife.'*

[3] Royal Society Meeting, 2003. Lord May http://www.gmsciencedebate.org.uk/meetings/pdf/110203-transcript.pdf

herbicide is that a range of both broad-leaved weeds (dicotyledons) and grass weeds (monocotyledons) can be controlled simultaneously, rather than using several different herbicides to control these different components of the non-crop flora.

Crops have been modified to be tolerant to a range of other herbicides. For example, oilseed rape and cotton have been modified to be tolerant to bromoxynil, and cotton and flax to sulfonyl urea. In the longer-term, the impacts of herbicide tolerant cropping in the UK may not be limited solely to the effects of glyphosate and glufosinate ammonium or to the products of GM plant breeding.

The potential impacts of weed control strategies offered by GM HT crops

Changes in the use of persistent herbicides

The environmental impact of broad spectrum herbicides

The two broad spectrum herbicides used most commonly in association with GM HT crops – and those that would most likely be used in the UK if approved – are glyphosate (e.g. 'Roundup') and glufosinate ammonium (e.g. 'Liberty'). Glyphosate is a systemic herbicide used for post-emergence, broad spectrum control of annual and perennial broad-leaved and grass weeds, and acts by inhibiting an amino acid metabolism pathway that exists in higher plants and micro-organisms, but not in animals. Glufosinate ammonium similarly provides post-emergence broad spectrum control, but of annual grasses and broad-leaved weeds, and acts by inhibiting an enzyme responsible for ammonia detoxification ultimately leading to the cessation of photosynthesis.

Glyphosate is already widely used in Britain, for example to clear weeds in stubbles before cropping or as a dessicant in oilseed rape, as well as in gardens and industrial sites. Glufosinate is used very occasionally for weed control on oilseed rape and potatoes. Crops that are tolerant to these herbicides allow the use of a single herbicide rather than a combination of several narrow spectrum herbicides, some of which are persistent in the soil. Both herbicides act mainly through contact with foliage, and are broken down rapidly in most soils (i.e. are non-residual).

The environmental impact of glyphosate is considered very low compared to many other herbicides on the market. Two studies (Dewar *et al.* 2003, Hin *et al.* 2001) have used the Millieumeetlat ('environmental yardstick') system (Reus & Leendertse 2000) to guage the environmental impact of glyphosate. In both studies, this system, which considers the toxicity, biodegradability and persistence of pesticides in the soil, rated glyphosate's environmental impact as very low compared to the herbicides used in a conventional beet or soybean weed control programme.

While glyphosate may itself be relatively harmless, some of the surfactants with which it has been formulated (to prevent the glyphosate from forming into droplets and falling off leaves) were somewhat more toxic, acting as irritants. More recent surfactants have none of these toxic effects.

These results broadly confirm those of field and laboratory toxicological studies which have shown that both glyphosate and glufosinate ammonium have low direct toxicity to invertebrates and vertebrates (Breeze *et al.* 1999, Haughton *et al.* 2001a & b, Edwards &

Bohlen 1996). Glyphosate may leach into watercourses, however, where it may present some fairly low risks to water-borne organisms (Hin *et al.* 2001), while glufosinate may be toxic to some soil micro-organisms (Quinn *et al.* 1993, Ahmed & Malloch 1995). Their toxicity is in general much lower than the several herbicides they may replace in controlling weeds in non-GM crops.

Changes in pesticide use

Determining whether chemical pesticide use declines, or is likely to decline, upon the introduction of GM HT cropping is complex (Heimlich *et al.* 2000, Carpenter *et al.* 2002, Hin *et al.* 2001, Phipps & Park 2002). It is even more problematical determining the environmental impacts of these changes in pesticide usage. Not only have different studies adopted different analytical methods, but what should be measured and how? Should it be changes in total herbicide use, or changes in the 'conventional' herbicides that the GM HT system replaces? Both are valid questions. Similarly, should use be quantified as, for example, total area treated or total quantities of active ingredients per unit area, and how can chemicals with different environmental impacts be compared meaningfully?

In Europe, the use of GM HT crops is projected to reduce the overall amounts of herbicide used (Coyette *et al.* 2002), however to examine the actual (rather than projected) impact it is necessary to look to the US or Canada where GM HT soybean and canola (oil seed rape) has been grown commercially since 1996.

The USDA[4] Economic Research Service estimates that overall (ie glyphosate plus conventional) herbicide use - measured as pounds of active ingredient per acre - increased by 3% due to the adoption of glyphosate-tolerant soybean (Lin *et al.* 2001). Between 1995 and 2000 the percentage of the total soybean acreage treated with glyphosate (use rate ~630 g/ha) rose from 20% to 62%, while that of the most commonly used 'conventional' herbicide (Imazethapyr, use rate ~70g/ha) declined from 44 to 12%. Similar trends were noted with other herbicides such as pendimethalin and trifluralin (Carpenter *et al.* 2002). The environmental impacts of these latter two herbicides were rated substantially higher than glyphosate by the Millieumeetlat system (Hin *et al.* 2001).

A separate study (Fernandez-Cornejo & McBride 2000), again of soybean, suggested that glyphosate use (pounds per acre) rose from 0.17 in 1996 to 0.43 in 1998, while all other herbicides combined fell from 1.0 to 0.57; the net result of this was that total herbicide use fell by about 10%. A review of various studies (Hin *et al.* 2001) suggested that change in overall herbicide use on GM HT soybean in the US during 1995-98 varied from a 7% increase to a 40% decrease, depending on the study concerned and the analytical method adopted. In Canada, a detailed analysis of grower experience with a range of HT canola varieties indicated a 39% reduction in herbicide costs compared to conventional cropping (Canola Council of Canada[5] 2001).

There is emerging evidence that weeds in GM HT crops may develop resistance to glyphosate (e.g. soybean; Carpenter *et al.* 2002). For example, within three years of using glyphosate in GM HT soybean at a site in Delaware, horseweed, an annual broad-leaved weed, developed resistance to it (VanGessel 2001). Herbicide resistance is not unique to GM cropping, however, and more than 200 weeds have been reported to be resistant to the herbicides that

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[4] United States Department of Agriculture

[5] **Canola Council of Canada** .2001. An agronomic and economic assessment of transgenic canola. http://www.canola-council.org

once controlled them (Carpenter *et al.* 2002). In addition, some weeds, for example late emerging ones such as waterhemp in soybean, are not controlled well by glyphosate (e.g. Baldwin 1999).

Given that one of the potential benefits of GM HT cropping is a reduction in pesticide use (both overall, and of more environmentally damaging pesticides), such problems may lead farmers to increase the rate and frequency of glyphosate application, or to re-introduce older, less benign herbicides alongside it (Bridges 1999, Duke 1999). Indeed, there is some evidence from the US that this is already happening (Baldwin 1999, Owen 1997, 2000); for example, the residual herbicide atrazine is sometimes used alongside glyphosate in controlling pernicious weeds in GM HT corn. The situation in the US, however, may not be the same as in the UK, particularly as agricultural rotations are more diverse in the UK, where farmers are unlikely to adopt US-style rotations with crops that are all tolerant to the same herbicide. The extent to which resistance to broad spectrum herbicides might become a problem in the UK remains unclear.

Thus, the evidence of whether herbicide use overall declines with the introduction of GM HT cropping is somewhat equivocal, although on balance it does seems that modest declines have occurred in the US and Canada in the short term. More importantly perhaps, it is likely that the more environmentally benign herbicide glyphosate has replaced some with higher environmental impacts. In principle, resistance to broad spectrum herbicides could, over time, counter some of these potential beneficial effects; whether or not this would happen in the UK is unclear. However impacts of herbicides on non-target biodiversity are not necessarily related to the amount of herbicide used, but to the efficacy and timing of use of the herbicide concerned, so we must be careful not to confuse inputs of herbicides with their impacts.

The simplicity of weed control

While there may remain some doubt whether GM HT cropping always increases farmers' yields or profits, it seems to be widely accepted that one reason farmers in North America favour GM HT crops is because weed management is simpler (Owen 1997, Firbank & Forcella 2000, Carpenter *et al.* 2002). Instead of using several herbicides to achieve adequate weed control, farmers can use a single herbicide to control a broad spectrum of weeds. On soybean in the US, farmers using GM HT cropping used fewer active ingredients (Benbrook 2001) and made fewer trips over each field, both of which made for easier management (Carpenter & Gianessi 2002). The fewer passes over a field brings with it other potential environmental benefits such as reduced energy costs and emissions. In a survey in Canada, half of all growers suggested that the main reason they chose to grow GM HT canola was because it was easier and provided improved weed control whereas less than 20% did so for higher yields and profits (Devine & Buth 2001).

The flexibility of weed control and potential biodiversity gains

Glyphosate and glufosinate ammonium are sprayed after weeds emerge (post-emergence) and may be more effective in controlling larger weeds than existing herbicides in the rotation. Because of this, the timing of their application is less critical than for conventional herbicides. This gives farmers increased flexibility in weed management; for example not worrying if spray dates are missed due to bad weather. In addition, because these herbicides are applied post emergence, farmers could choose only to spray those areas that most need it, rather than spraying the entire field. In principle, a farmer could wait to see if weed burdens were low in a particular year, and might decide not to spray at all. Such a strategy is less practical with pre-emergence conventional herbicides. There is little evidence to support this assertion, however, as most farmers seem to follow the herbicide manufacturer's labels, which suggest one or two applications.

Two separate studies, one in Denmark (Strandberg & Pedersen 2002) and one in England (Dewar *et al.* 2003) have used the flexibility in application dates provided by glyphosate to attempt to deliver biodiversity gains. Each of these studies compared the biodiversity associated with plots of conventionally grown beet, with that associated with plots of GM HT beet with varying glyphosate application dates.

In the Danish study of fodder beet, the GM 'Roundup Ready' plots held improved populations of weed flora and arthropod fauna compared to conventionally treated plots early in the season. The greater the delay in application of the first glyphosate spray, the greater the improvements in flora and fauna. Conventional plots held fewer weeds, but at least a proportion set seed; in the Roundup plots no seeds were set following applications of glyphosate. This study was restricted to a single season, so the impact on the weed seed bank, and on weed populations in following crops were not measured, although lack of seed set suggests that routine cropping using Roundup Ready beet could have a dramatic effect on weed population as there would be no recruitment from that season's crop. In addition, food resources for seed predators (e.g. some invertebrates and small mammals and granivorous birds) would be markedly reduced.

The English study (Dewar *et al.* 2003) used band-spraying, in which glyphosate was sprayed along, but not in-between, rows of glyphosate-tolerant sugar beet. By band spraying, those weeds that directly compete with the crop could be controlled - thus ensuring yield losses are reduced - while allowing weeds to grow in the rest of the field. Theoretically, by band spraying over GM HT beet, weeds in between rows could be allowed to grow to a substantial size, before being killed by a second spray of glyphosate over the entire crop. The occurrence of abundant weeds in the crop, it was argued, could provide resources for invertebrates important in the diet of declining farmland birds. Although the design of this study was complex, and the statistical treatments sometimes unclear, there was evidence – across treatments – that when more weeds were left in a plot, numbers of some arthropods were higher. However, this was not true of all faunal groups, nor did the results hold at all study sites. In addition, the evidence that band-sprayed plots specifically held greater weed and invertebrate abundance than conventional plots was weak.

The most potentially interesting result of this study was that band spraying allowed subsequent spraying of the entire crop to be delayed without significant reductions in yield compared to conventional treatments. However, yield was nevertheless greatest in those plots with normal GM management (i.e. early application of glyphosate and no band spraying), which contained lower weed and invertebrate populations than conventional treatments. Thus, despite media coverage of this study - which suggested that GM HT crops would benefit skylarks – it actually demonstrated that unless farmers were willing to risk a yield loss, then the management that they would most likely adopt would reduce weed and invertebrate abundance compared to conventional management. The greater flexibility afforded by such GM HT crops provides an opportunity to explore more creative management regimes, provided they can be enforced.

Unfortunately, this study did not investigate the impact of treatment on seed set and on following crop weed populations.

Changes in the extent of mechanical tillage

Traditionally, mechanical tillage has been used to control weeds and prepare seedbeds. However, it also leaves the ground exposed to wind and water erosion that can carry fertile soil and agricultural chemicals into watercourses (Carpenter *et al.* 2002, Fawcett & Towery 2002). It is argued that GM HT cropping could favour a reduction in mechanical tillage (Carpenter *et al.* 2002, Fawcett & Towery 2002, Firbank & Forcella 2000) as weeds are controlled with broad spectrum herbicides instead, and the subsequent crop could be planted into the stubble of the previous crop without ploughing. Such reduced tillage, it is argued, could provide a wide range of environmental benefits, ranging from reduced soil erosion, through carbon sequestration into the soil to increased biodiversity.

Arguably, the most obvious benefit of reduced mechanical tillage is that it leaves more crop residue on the soil surface, protecting the soil from the erosive impacts of wind and rain (Laflen *et al.* 1985). 'No-till' systems that leave nearly all plant residue in place and can reduce erosion by 90 percent (Hebblethwaite 1995, Fawcett 1994). Because tillage increases the availability of oxygen, it speeds the decomposition of soil organic matter and releases CO_2 – a greenhouse forcing gas – into the atmosphere. A reduction in mechanical tillage increases the ability of soil to sequester carbon, thus reducing CO_2 emissions. A ten-year study in the US showed that the emissions of greenhouse gases were about eight times higher on conventionally tilled land than on no-till land (Robertson, Paul and Harwood 2000). The biodiversity benefits of reduced mechanical tillage are less clear, although some studies have suggested it could be beneficial for wildlife, too. Tillage harms earthworms by burying food sources and destroying burrows, thus earthworm populations increase as tillage is reduced (House and Parmalee 1985). Similarly, several studies have shown that no-till row crops may hold higher densities of birds than conventionally tilled crops (Basore *et al.* 1986, Warburton & Klimstra 1984). Whether or not reduced tillage favours biodiversity more broadly is unclear; some taxa may be favoured others disfavoured. The biodiversity impacts of reduced tillage is currently an active area of research.

There is some evidence that 'no-till' acreage increased following the introduction of glyphosate-tolerant soybean. In the US, no-till soybean acreage rose by 35% (Conservation Technology Information Center 2000) or 111% (American Soybean Association 2001) between 1995 and 2000. In Argentina, it rose by 57% between 1996 and 1999 (James 2001). In each study, the rise in no-till was attributed to the adoption of glyphosate tolerant soybean. In the US, however, the overall level of conservation tillage (of which no-till is the most soil conserving form) has not changed. In Canada, an analysis of grower experience with a range of HT canola varieties indicated a 12% reduction in operational costs associated with less tillage (Canola Council of Canada 2001)

Whether or not GM HT cropping would lead to reduced tillage in the UK is unknown. The use of differing tillage regimes in UK is influenced by soil type (Cannell *et al.* 1978) and so reduced tillage may not be practical in some soil types, even were GM HT cropping practiced. In addition, some of the benefits of reduced tillage (e.g. carbon sequestration) are only apparent when practiced throughout the whole rotation and over long periods. While this may occur in the US, it would be unlikely in the UK where, in the short to medium term at least, only one crop in the rotation is likely to be GM HT - the break crop.

While GM HT cropping may favour it, reduced tillage nevertheless brings a range of benefits – outlined above - that could influence its adoption in the UK in the absence of GM HT cropping, i.e. within conventional agriculture.

Changes in damaging agricultural operations

It has been suggested that GM HT cropping, could favour a reduction in agricultural operations (such as mechanical weeding or number of tractor passes) that may be damaging to ground nesting birds during the breeding season. While it may be the case that agricultural operations can be damaging to nesting birds (e.g. Green 1988), and that fewer herbicide applications are needed in GM HT crops (see above). Studies are needed to deterimine whether or not these changes can lead to increased nest survival.

Pest diversion to non-crop flora

One study (Dewar *et al.* 2000) has suggested that, as GM HT cropping may allow weeds to be maintained for longer than under conventional cropping, aphids may be provided with a larger non-crop food resource, thus potentially reducing damage to the crop and usage of aphicides.

Wildlife food web impacts

Arguably, the most important concern surrounding the introduction of GM HT crops in Britain is that their weed control programs may be so efficient that they will further exacerbate the declines of the weed flora, and the farmland wildlife that depend on it (English Nature[6] 1998, 2000, Hails 2000, Dewar *et al.* 2003, Andreasen *et al.* 1996, Buckelew *et al.* 2000, Watkinson *et al.* 2000). Given its importance, a summary of the evidence of these declines over the last few decades, and their causes, is provided here.

Declines in farmland biodiversity

Evidence

The decline of arable biodiversity has been well documented (Robinson & Sutherland 2002). While the most detailed information comes from birds, there is considerable information on declines in the arable weed flora and growing information on declines of invertebrates.

The long-term (post 1970) declines in population and range of farmland birds first became apparent in the late 1980s (Baillie *et al.* 2001, Gibbons *et al.* 1994, Fuller *et al.* 1995) and subsequently (Siriwardena 1998a, Chamberlain *et al.* 2000). The UK government's headline 'Quality of Life' wild bird indicator summarises this decline very succinctly[7] (Gregory *et al.* 2003) and it continues, albeit at a slower rate than in the 1970s and 1980s.

Although the information on declines in population of arable plants is less detailed, if anything their contractions in geographic range have been even more dramatic (Preston *et al.* 2002), and there are well documented recent changes in plant diversity (Barr *et al.* 1993; Haines-Young *et al.* 2000) and abundance (Smart *et al.* 2000, Wilson 1992, Wilson 1999,

[6] **English Nature.** 1998. Government wildlife advisor urges caution. http://www-english-nature.co.uk/news/story.asp?ID=139 Peterborough: EN.
English Nature. 2000. English Nature continues to back trials of GM crop. http://www-english-nature.co.uk/news/story.asp?ID=195 Peterborough: EN.

[7] http://www.sustainable-development.gov.uk/indicators/headline/h13.htm

Wilson *et al.* 1999, Firbank & Smart 2002). Non-crop plant communities have changed so that, generally, broad-leaved weeds have declined and grasses increased (Chancellor 1985, Firbank 1999). Fourteen of the 62 vascular plants in the UK. Biodiversity Action Plan are exclusive to farmland. Some of these species are now extremely rare in the countryside, whereas a few decades ago they were regarded as important economic weeds of arable systems. In addition, the overall size of the seed bank in arable soils has declined markedly in Britain (Robinson & Sutherland 2002). Such declines in arable flora are not restricted to the UK (e.g. Andreasen *et al.* 1996).

Information on population and range trends among invertebrates are less well documented. The most detailed study of long-term trends in invertebrate numbers – from Sussex (Aebischer 1991, Ewald & Aebischer 1999) – shows that most groups declined. While another long-term study from Rothamsted shows that farmland moths have declined similarly (Woiwod & Harrington 1994), butterflies that occur widely on farmland have increased (even though those with more restricted distributions have declined; Greatorex-Davies & Roy 2001, Asher *et al.* 2001). Bumblebee populations also declined over the last half-century (Williams 1986).

Broadly, across all taxonomic groups, the available evidence suggests that there have been widespread declines in the populations of many organisms associated with farmland in Britain, and that these declines have been most marked among those that are farmland habitat specialists; many of those still common on farmland are habitat generalists (Robinson & Sutherland 2002).

Causes – focussing on the link between biodiversity loss and herbicide use

There is a growing body of evidence that suggests that these declines in biodiversity are related to intensification of agriculture (Robinson & Sutherland 2002). Again, some of the best examples come from studies of birds (Krebs *et al.* 1999, Chamberlain *et al.* 2000, Donald *et al.* 2000), although there is also evidence from plants (Wilson & King 2000, Wilson 1999).

Given that the most direct change in management upon the introduction of GM HT crops would be the more widespread introduction of broad spectrum herbicides, it is important to be able to tease apart the impacts that herbicides *specifically,* rather than a range of other factors (e.g. autumn sowing, loss of mixed farming, loss of farm features such as hedges and ponds), have had on these biodiversity declines. This is not straightforward, as teasing apart these various effects – even within the chemical inputs alone – is best undertaken by experimental studies which are frequently lacking.

The increase in use (particularly in the 1970s and 1980s) and effectiveness of herbicides specifically aimed at removing weeds from cropped areas has resulted in reduced weed populations (Aebischer 1991, Campbell *et al.* 1997, Cooke & Burn 1995, Wilson 1992) and resulting soil seed banks (Jones *et al.* 1999, Robinson 1997, Robinson & Sutherland 2002). The use of herbicides is frequently associated with reduced species diversity and reduced abundance of non-crop herbaceous plant species on agricultural land (Marshall 1991, Jobin *et al.* 1997). Experimental evidence for the effects of herbicides has suggested that they lead to a reduction, rather than an elimination, of weed populations (Cousens & Mortimer 1995). Conversely, experiments in which herbicide inputs are reduced show that the seedbank and flora can recover (Moreby & Southway 1999, Squire *et al.* 2000). Many species that remain common on farmland are either resistant to, or difficult to target with herbicides, or have prolific persistent seed banks, suggesting that herbicides are likely to be responsible for declines of the remaining species (Robinson & Sutherland 2002).

A wide range of organisms depends on the non-crop plants within cropped areas, and there is evidence that changes in the arable flora can affect these other taxonomic groups. The non-crop vegetation provides resources directly to herbivorous insects, as well as to seed predators such as birds and beetles. It supports many invertebrates that themselves provide food for vertebrates (e.g. Potts 1986, Pollard & Relton 1970) and other invertebrates (Bohan *et al.* 2000). Numbers of some invertebrate groups, particularly carabids and staphylinids can be greater with increasing amounts of non-crop vegetation (Lorenz 1995, Dewar *et al.* 2003, Strandberg & Pedersen 2002) and in the absence of herbicides (Raskin *et al.* 1994). Experimental studies have shown that increases in herbicide applications to cereal crops led to a decline in grey partridge chick survival through the removal of chick invertebrate food host plants (Potts 1986, Sotherton 1991), and this has been the primary cause of the partridge's decline.

The declines of populations of seed-eating farmland birds have received much attention recently. Declines of these species have largely been driven by changes in over-winter survival (Siriwardena *et al.* 1998b, Siriwardena 2000), a period when these species rely heavily on non-crop seeds for food (Moorcroft *et al.* 2002, Robinson & Sutherland 2002). Experimental provision of seed food at this time can increase over-winter survival (Hole *et al.* 2002).

Direct experimental evidence linking the declines of farmland birds to increased levels of herbicide use is available only for the grey partridge. The chain of evidence linking declines in broad-leaved weeds as a consequence of herbicide use, the use that birds make of weed seeds, and the declines in bird populations, however, make a strong circumstantial body of evidence that suggests that further declines in weed seed resources are likely to exacerbate farmland bird declines as well as those of other species dependent on this resource.

Efficiency of weed control

A range of studies in the UK, Netherlands and US have shown that broad spectrum herbicides used in conjunction with GM HT beet (Read & Bush 1998, Strandberg & Pederson 2002, Wevers 1998), maize (Read & Ball 1999a), oilseed rape (Read and Ball 1999b) and soybean (Buckelew *et al.* 2000,Culpepper *et al.* 2000) can provide substantially more efficient and more reliable (e.g. less dependent on weather conditions) weed control than conventional herbicide regimes. By contrast, one study has suggested that weed control is sometimes less successful when growing GM HT varieties than when cultivating conventional varieties (Firbank & Forcella 2000).

Herbicides can also effect the vegetation of field boundaries. One study in England has shown that glyphosate damaged hedgerows and field margins, removing perennial species, allowing colonisation by annuals (Sweet & Shepperson 1998). The application of broad-spectrum herbicides over GM HT crops occurs during the peak growing season in field margins, when they are at their most vulnerable to the effects of spray drift, although, compared to selective herbicides, the timing of application is less critical allowing more choice in weather conditions.

Evidence from the US suggests that GM HT cropping can lead to marked changes in the overall weed community with time, for example favouring those that seed before the broad spectrum herbicide is applied, or which germinate after herbicide application (Derksen *et al.* 1999, Forcella 1999, Owen 2001). Thus, weeds populations may not be reduced by GM HT cropping, rather they may be changed. The impact that such chronological shifts might have on the taxa that rely on weeds as a resource is unknown.

Effects on other taxa

These changes in the efficiency of weed control could have important knock-on effects on other taxa that are dependent upon them. Few studies have investigated the effects of GM HT cropping on biodiversity; most studies have been small scale with equivocal results (Buckelew 2000, Jasinski *et al.* 2001, Ruiz *et al.* 2001). Given the extent of GM HT cropping in North America, it is a great pity that there are so few published studies on its biodiversity impacts. The likely reason for this is that in North America agriculture and wildlife are catered for in geographically distinct areas, whereas in the UK wildlife and agriculture are expected to share the same ground.

The two most important effects on biodiversity of broad spectrum herbicides could act in opposing directions. The delay in herbicide application could allow more weeds to live in fields for longer early in the season; this might favour invertebrate populations some of which might be important prey for vertebrates. Conversely, the efficiency of control may reduce the number of weeds late in the season, and the number that set seed, thus reducing important food resources for seed predators and reducing weed populations over time.

As outlined earlier, there is a small amount of evidence that delayed weed control can lead to improvements in some invertebrate populations at some sites early in the season (Strandberg & Pedersen 2002, Dewar *et al.* 2003). There is no evidence that these modest increases in invertebrates favoured taxa at the next trophic level. Neither study specifically investigated impacts on those elements of the invertebrate fauna important in the diet of vertebrates, such as birds, even though their diets are well known (e.g. Wilson *et al.* 1999). Neither study investigated the effects on vertebrate populations directly, thus the assertion that improved invertebrate populations might lead to more birds remains hypothetical. In addition, GM HT cropping does not always favour invertebrates; a study in the US showed that invertebrate numbers were lower in plots of glyphosate-tolerant soybean than in conventional plots (Buckelew 2000).

More concerning is the impact on weed seed resources and weed populations. Few studies have compared seed set in conventional and GM HT treatments. In the Netherlands (Strandberg & Pedersen 2002), the effect was dramatic with no seed set at all in GM HT treatments, but some in conventional treatments. No studies have examined weed seed bank and weed populations in following crops to determine the long-term effects of GM HT cropping however, in cases where no seed is set at all then the seedbank will eventually be depleted.

The potential impact of reduced weed seed resources and weed populations on vertebrates has been modelled (Watkinson *et al.* 2000) using the skylark *Alauda arvensis* and the weed fat hen *Chenopodium album,* the seeds of which are an important component of the skylark's diet (Wilson *et al.* 1999). The model allowed calculation of the impact of herbicide use on weed seed production and thus skylark numbers, and concluded that effects on local field use by birds might be severe as fat hen populations declined due to the use of glyphosate. The model showed that the greater the degree of weed control in GM HT cropping compared to conventional, then the greater its deleterious impact on skylarks. More subtly, it also showed that the pattern of uptake of GM HT crops would greatly affect the overall impact on farmland biodiversity, as the results were dependent on whether farmers with weed-rich or weed-poor fields were more likely to adopt GM HT cropping.

While this model has been criticised for its simplicity (e.g. Firbank & Forcella 2000, Carpenter *et al.* 2002), it provides an elegant insight into the concerns for biodiversity conservation, and modelling of this sort could provide a powerful tool to assess the long term possible impacts of GM cropping on UK biodiversity.

The central issue as to whether GM HT cropping will be more or less harmful to wildlife than conventional cropping revolves around the relative importance of these two contrasting impacts. Will delayed application in GM HT crops allow more weeds, more invertebrates and, for example, improved breeding productivity of birds? Or, will the efficiency and reliability of weed control mean fewer seed resources for seed predators such as granivorous birds, and declining weed populations in the long term? Expressed more simply for birds, is there any point in providing insect food for chicks in the summer that will subsequently starve as adults over-winter because of lack of seeds. Given that populations of seed-eating farmland birds seem to be limited largely by winter food resources (Siriwardena *et al.* 1998, Siriwardena 2000, Hole *et al.* 2003, Robinson & Sutherland 2002), ensuring that abundant weed seeds are retained in the arable environment could well be more important than improving the availability of chick food.

6.5.4 Is there general scientific agreement?

There is general scientific agreement in some areas regarding the impacts that the changed weed control strategies resulting from GM HT cropping will have on the environment, but not in others.

It is generally accepted that the broad spectrum herbicides (e.g. glyphosate) used in association with broad spectrum HT (whether GM or non-GM) crops are more environmentally benign than many of the conventional herbicides that they would replace. This benign character does not extend to the impact on their target organisms (i.e. weeds) and dependent food webs.

There is some debate about whether overall herbicide usage will decline consequent upon the introduction of GM HT cropping, although the emerging scientific opinion – mostly from North America - seems to be that modest declines are likely. Evidence, again from North America, that the more environmentally damaging conventional herbicides will be phased out over time is stronger.

It is generally accepted that GM HT weed control strategies are simpler for the grower than conventional cultivation. Similarly, they seem to offer the grower more flexibility, particularly in application dates. There is no evidence that farmers alter their GM HT weed control strategy based on observed weed burdens, even though this is possible in principle.

While delayed herbicide application dates in GM HT crops could deliver enhanced non-crop biodiversity, there is only limited evidence that it does, and substantial disagreement about whether what it can deliver is important to biodiversity conservation or not.

There is general agreement that reduced tillage can deliver a wide range of environmental benefits, and there is evidence from the US that GM HT cropping can favour reduced tillage techniques. It is entirely unclear whether GM HT cropping in the UK would lead to a renewed interest in reduced tillage as its application is constrained by soil type and other factors.

There is no evidence to judge whether GM HT cropping increases the productivity of ground-nesting birds through reduced agricultural operations.

There is general agreement that there has been a substantial decline in biodiversity in recent decades. The evidence is stronger for birds and plants than for invertebrates. There is growing scientific acceptance that these declines have been caused by agricultural intensification. There is less evidence (particularly experimental), and therefore less general agreement, to indicate the relative contribution of herbicides *per se* in these declines. There is, however, general agreement that the decline in weed seed resources has played a major causal role in the dramatic declines of seed-eating farmland birds.

There is general agreement that GM HT cropping can provide more efficient and reliable weed control than conventional regimes. Crucially there are differing views about how farmers would use GM HT crops in terms of frequency and timing of herbicide applications, so it is unclear whether GM HT cropping will result in more effective weed control. The Field Scale Evaluations may shed some light on this issue.

There is substantial disagreement about the biodiversity impacts of GM HT cropping. This is because the relative importance of the potential biodiversity gain from improved weed populations early in the season, and potential losses from reduced weed seed resources late in the season and reduced weed populations in the long-term, are largely unknown.

6.5.5 Is this issue unique to GM?

The potential changes in weed management strategies outlined above are due to the introduction of different herbicides as alternatives for farmer decisions, and not to the genetically-modified herbicide tolerant crops *per se*. Herbicide tolerant crops have been developed using conventional plant breeding techniques, and thus herbicide tolerance is not unique to GM. For example: atrazine tolerance in corn, triazine tolerance in rape, imidazolinone tolerance in corn and wheat, and chlortoluron tolerance in wheat were all developed using conventional methods (Mazur & Falco, 1989). Recently there is the development of a glyphosate tolerant rygreass by non-GM breeding (Johnston *et al.*1989) that could present similar challenges to those being considered here.

However, GM techniques have allowed the development of several crops that are tolerant to several broad spectrum herbicides, whereas conventional breeding techniques have not so far allowed such radical developments. Because of this, many of the issues surrounding crops that are tolerant to broad spectrum herbicides are currently primarily relevant to GM.

Some of the environmental benefits that may accompany GM crops, such as low-tillage farming and a reduction in use of more harmful pesticides can be accomplished without GM crops. For example, interest in, and use of, low-tillage farming is increasing in the UK regardless of the GM debate[8]. Similarly, there are alternative ways to reduce the use of some of the more environmentally damaging herbicides that may be replaced if GM crops are given commercial approval. These include introducing pesticide taxes or greater regulation.

6.5.6 Are there gaps in our knowledge or scientific uncertainties, and are these important?

Unquestionably, the largest gap in our knowledge is the impact that GM HT cropping would have on biodiversity. Given the lack of studies in the US and Canada (and, in any case, the different species of wildlife and different approaches to farming that are involved) there is insufficient information from other parts of the world to form a scientifically valid assessment of the impact of the introduction of any particular GM crop on UK biodiversity. Nor would studies from elsewhere in Europe, should they exist, necessarily provide a sufficiently detailed picture to inform UK approvals since species differ in distribution, ecology and status across the EU. Thus, the large-scale crop-specific field trials carried out are important to assess any impacts (positive or negative) of GM crops on UK biodiversity, and ongoing monitoring should form an important part of the process of commercial approval of individual GM crops in the UK.

Given that the UK government is increasingly favouring demonstrably sustainable forms of agriculture, and that it has committed itself – via Public Service Agreements – to reverse the fortunes of farmland wildlife, a much better understanding of the biodiversity impacts is required. Studies that examine the impacts of GM cropping at a field or farm scale and over several seasons are clearly required. Such studies should be undertaken increasingly on land away from agricultural research establishments, thus allowing a better approximation of day-to-day farming practices.

The case for the introduction of GM HT crops would be strengthened if the evidence of reductions in overall herbicide usage were less equivocal. Such data will become available with longer runs of data from North America. Similarly, there is a need for further analyses of long-term changes in usage of conventional herbicides, and importantly the impacts these might have on the biotic and abiotic environment.

It would be useful to further quantify the extent to which GM HT cultivation allows for simpler weed control. It would be valuable, for example, to obtain information from more crops of the number of applications, the number of active ingredients used and the number of tractor passes needed.

An analysis of the likely uptake of reduced tillage consequent upon the commercial introduction of GM HT crops in the UK would be informative, in particularly how this might be influenced by soil type. Further evidence of the biodiversity impacts of reduced tillage would help inform this debate.

Improved monitoring of, particularly, non-avian taxa would strengthen arguments about declines of species associated with the arable environment. In some cases this may be the introduction of new schemes, in others the analysis of existing data. Arguably, much of this is

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[8] see e.g. http://www.gct.org.uk/research/icm/frameset.html , http://www.fwag.org.uk/LocalGroups/Gloucestershire/news.html and http://www.pan-uk.org/pestnews/pn24/pn24p3.htm

already in hand. Should GM crops be commercialised, this monitoring must continue to ascertain their impact on biodiversity.

With the exception of maize, the GM HT crops that are nearest to commercialisation in the UK are grown as break crops. If more than one GM crop was grown in a rotation the effects could be cumulative. Because of this a much better understanding of changes in weed populations throughout an entirely GM rotation is needed.

Were GM HT crops commercialised in the UK, it is largely unclear how they would be adopted. Would only farmers with particularly heavy weed burdens adopt the technology, or would it be adopted more broadly? In the US there is evidence of a widespread uptake of GM cropping irrespective of weed burdens (Fernandez-Cornejo & McBride 2002). It would be valuable to ascertain the likely adoption of GM cropping in the UK, only then can its likely overall impacts be predicted.

6.5.7 Likely future developments

The immediate future will see the publication of the initial results of the UK government funded farm-scale trials of GM HT crops (Firbank *et al.* 2003, Perry *et al.* 2003). These trials were established to investigate the impact of the management of these crops on farmland biodiversity in Britain. Three separate crop types have been investigated, beet (sugar and fodder), maize, and oilseed rape (spring and winter-sown). The trials have concentrated on the effects of the broad spectrum herbicides associated with the GM HT crops and contrasted this with the weed management of comparable conventional varieties. The experimental design involved halving fields and sowing half with a conventional variety and half with a GM HT variety of the same crop. Measures of abundance and diversity of a wide range of taxonomic groups were obtained from within the field and at field margins before, during, and after crop growth and in following crops. Fieldwork was undertaken during 2000-03, and results of the spring-sown crop studies are due in late summer 2003, with the results of winter-sown oilseed rape following in 2004.

The results of this study will help provide answers to many of the questions related to the impact of GM HT crops on biodiversity (and more broadly). In particular, the large scale of the FSEs, both spatially (with ca 60-75 fields of each crop type planted throughout Britain on farms of varying intensity) and temporally (over several seasons, with measures taken in following crops) will overcome many of the problems associated with previous studies of the impact of GM HT cropping on biodiversity.

Despite this, the FSEs will not answer all outstanding scientific questions. The FSEs have only studied break crops and maize, and not an entire GM HT rotation, so cumulative effects over many seasons cannot be investigated (although the FSEs will provide some information on continuous GM HT forage maize). The FSEs only studied normal GM practice, i.e. by following the manufacturer's labels to ensure cost-effective weed control; they do not examine novel techniques (such as band-spraying) that could be developed to favour biodiversity but nor do they study non-compliance of recommended procedure. They compared current conventional herbicide regimes with GM HT cropping. Should conventional regimes change (for example with potential EU legislation phasing out more environmentally damaging herbicides) then the relative impacts of GM versus conventional may also change. In addition, some of the wider environmental impacts, such as a reduction in tillage, could not be studied.

Some of these outstanding issues are being investigated within the BRIGHT[9] project (Sweet & Griffith 2002). This six-year trial, commenced in 1998, while mainly exploring agronomic issues such as the persistence of HT volunteers and the evolution of multiple tolerance in oilseed rape, is also investigating the impact of broad spectrum herbicides on botanical diversity across rotations.

Given the paucity of UK information on the impacts of GM HT crops on biodiversity, and the imminence of the publication of the initial findings from the FSEs, we will return to this issue in more detail in our second report.

The GM HT crops currently under consideration for UK commercial approval could be followed by GM HT wheat and grass (for both amenity and livestock farming) in several years time. Wheat and grass together cover more than half of UK farmland and therefore much larger areas of land would be concerned. In the case of wheat, GM HT wheat could potentially lead to a reduced need for break crops such as oil seed rape, peas, beans etc in UK agriculture and this would reduce landscape variety, and, almost certainly biodiversity, in the countryside. In addition, being able to grow GM HT wheat in rotation with GM HT oil seed rape could lead to very dramatic and rapid further reductions in non-crop arable flora. GM grasses, particularly but not only GM HT grasses, could also greatly reduce floral diversity on livestock farms. Such potentially major changes to farming practice would be likely to have impacts on biodiversity and these would need to be assessed under current regulations before commercial approval could be given.

6.5.8 Where there is important scientific uncertainty, what is the way forward?

Research

There remains scientific uncertainty over the impacts, positive or negative, of GM HT crops on UK biodiversity simply because few studies have been published to address this area of concern. The establishment of the FSE programme indicates the type of study needed to assess biodiversity impacts at the farm scale. However, as noted above, it is unlikely that the FSE programme will address all of the concerns about GM crops outlined at the beginning of this chapter. The regulatory process includes risk assessment, risk management and post market monitoring steps. The post market monitoring could be an important contributor to the overall understanding of environmental effects as the products are used in practice, in the event of commercial approval. Appropriate measures and indicators for simple and robust monitoring systems could prove valuable both for practical application and to test and improve generalisable mathematical models.

Only a few studies have endeavoured to develop novel management techniques for GM HT crops that specifically favour biodiversity. Should GM crops be commercialised in the UK, then it would be valuable to investigate such techniques further.

[9] Botanical and Rotational Implications of Genetically Modified Herbicide Tolerance

Although it is hoped that the FSEs will provide information on the likely impacts of GM HT cropping on higher vertebrates, for example birds, there would still be merit in developing the Watkinson *et al.* (2000) model, using parameters obtained from the FSEs, specifically. Such a model could potentially provide a powerful general predictor of the likely impacts of new cropping systems on wildlife and farm productivity.

Regulatory

It is possible to imagine situations where harmful impacts on wildlife have not been established beyond doubt (perhaps because none really exists) and yet concerns remain in the minds of the public and some scientists. Cautious commercial approval might be a way forward, which would involve post-release monitoring.

It is sometimes suggested that if GM crops are higher yielding and/or more profitable for farmers to grow then areas could be set aside from active production in order to deliver biodiversity benefits. Such measures would rarely be in the individual farmer's economic interest but could be imposed through the regulatory process through 'cross-compliance'.

6.6 HORIZON SCANNING

Apart from herbicide tolerant crops, what are the major new traits that might give rise to significant environmental impacts, positive or negative?

6.6.1 Summary

Assessment of the timescale and magnitude of new product introductions and their effects becomes more difficult the longer the timescale being considered. AEBC has carried out a thorough horizon scan[1] which illustrates the range of possibilities whilst highlighting the uncertainties inherent in such an analysis.

In the shorter term, most of the products in current registration processes for possible use in the UK are for import use (for food, animal feed or fibre) or for herbicide tolerance. This reflects the international nature of agriculture and food. The environmental impact of these crops in their country of growing is also of interest in informing the public debate. Potential positive impacts from virus and insect resistance are reductions in pesticide use; this is significant and well documented in cotton, more marginal in maize for corn borer resistance and yet to be measured for corn rootworm resistance. Potential negative impacts in development of resistant insect populations are dealt with in 6.4.1 of this chapter. Potential negative effects on non-target insects (Monarch butterflies) have so far been demonstrated to be minimal. Within a 10 year period, there is the possibility of introduction of crops resisting fungal attack (wheat, potato) or viruses (sugar beet, tomato, cucurbits or potato). Potential positive impacts are reduction of pesticide use. Potential negative impacts on non-target organisms such as soil fungi. Crops with improved quality (shelf-life or nutrition) are most likely to be imported.

The potential products from work currently at the research stage cover a much broader scope, but with a longer development time. Arable, minor or tree crops designed to produce specific non-food products (pharmaceuticals, speciality or bulk chemicals, biomass for energy or paper-making) are anticipated. Positive impacts in terms of renewable sources of industrial feedstaocks and diversification of farm crops and sources of rural income might ensue. Negative impacts could arise from direct effects of the novel crops on wildlife, or indirect effects on patterns of land use arising from large-scale adoption of such crops.

Traits with the potential to improve crop production in marginal environments (eg tolerance of drought, heat or salt stresses) could be anticipated to have major benefits to growers in those environments, including the developing world. Potential negative impacts could be direct, from making crops more successful as weeds or indirect from the changing the economic drivers to improve and cultivate areas with wildlife and conservation value. An example could be a highly productive grass which changed hill farming productivity.

The horizon scan has identified the paucity of baseline data and models at different scales from field to landscape agro-ecological systems as the basis for future assessment of larger scale environmental effects which could be useful across a broad range of policy making issues relating to land use and the rural economy. Most of the issues foreseen are not unique

[1] **AEBC.** 2002. Looking Ahead: An AEBC Horizon Scan.
http://www.aebc.gov.uk/aebc/reports/horizon_scanning_report.htm

to GM and will be driven by the economic decisions relating to the context of UK farming and food production. These are largely political rather than technical factors.

6.6.2 Background

This section addresses the potential environmental impacts of new[2] (at least to the UK) GM crops and products. The Agricultural and Environment Biotechnology Commission (AEBC) has undertaken a horizon-scanning exercise in 2002, to examine future developments (AEBC. 2002), much of which is still very relevant. Many website contributions have addressed this area as well as being covered in the public meetings[3] .

New crops and plant products are considered in three groupings.

- Crops and traits already commercialised or in late registration somewhere in the world.

- Crops and traits for which some product-related information is already available and there will have been some history of environmentl release. These are likely to be commercialised later in the 10 year horizon.

- Finally, traits which are currently in the research or experimental phase are more most likely to be commercialised, if at all, on a longer time horizon. .

In each of these areas the amount of field information from the UK is likely to be limited or non-existent. We have not considered GM microbes or animals.

6.6.4 Range of Views and Quality of Evidence

Earliest commercialisation: crops and traits already commercialised or in late registration elsewhere

The crops and traits in the earliest category of potential commercialisation listed on the agbios website[4]. Apart from herbicide tolerance traits they are likely to be :

(i) Maize with insect resistance (European corn borer and other Lepidopteran pests)
(ii) Maize with resistance to corn rootworm (soil coleopteran pest[3])
(iii) Cotton with insect resistance
(iv) High yielding oilseed rape hybrids
(v) Squash with virus resistance

The major environmental impacts anticipated with these developments are considered below.

Insect resistance (traits i-iii):

At present these traits are not directly relevant to the UK

[2] All traits considered are new to the UK, but are not confined to those of potential UK commercial importance. Some of the traits considered are currently being grown commercially by other countries.
[3] Refer to GM Scienec Review http://www.gmsciencedebate.org.uk/topics/forum/default.htm for full list.
[4] http://www.agbios.com/dbase.php?action=ShowProd&data=MON63

Potential Positive Impacts: reduced insecticide use The existing information from multi-year field and commercial experiences with cotton (USA, Australia) has supported the contention of reduced insecticide use (Phipps *et al.* 2002**,** Gianessi *et al.* 2002[5]) and web contributions [6, 7, 8]. This has also been seen in South Africa (Thomson J. 2001) and India[9]. In addition, higher yields of maize and better returns to farmer where insecticide use to control European corn borer is uneconomic (Gianessi *et al.* 2002). Higher yields of cotton and better economic return to cotton farmers in US, china, South Africa and India .

Potential Negative Impacts: Development of resistant insect populations (see 6.4 which deals specifically with this issue). Insect resistance management tools have so far avoided this eventuality in USA and Australia (Tabashnik *et al.* 2002, Monsanto. 2003). Potential Effects on non-target insects and predators has been a major cause for concern, based on lab studies (Losey *et al*. 1999), but subsequent field-based research has shown a neutral or positive impact, for instance in sweetcorn (Musser *et al.* 2003), maize (Pimental *et al*. 2000), and cotton (Carriere *et al*. 2003).

High yielding varieties (iv)

The high yielding oilseed rape is designed for increased productivity from hybrid vigour. The trait itself provides cost-effective production of hybrid seed through a sterility mechanism (Mariani *et al*. 1990).

Potential Positive Impact: Increased productivity and farmer income, more efficient land use.

Potential Negative Impact: Gene flow of sterility system components. Section 7.3 in the gene flow addresses this issue, where two key questions were raised. (i) Is the segregation of the sterility genes in pollen from the F_1 hybrid plants going to lead to an enhanced gene flow? And (ii) Could the sterility genes cause harm to populations of wild relative?

Virus Resistance (v)

Squash with virus resistance has been commercially grown in USA for some years. The potential is there for varieties to be developed for EU markets by backcrossing from the same events .

Potential Positive Impacts: Indirect effects could be seen in (a) reduction in pesticide use to control insect vectors (tomato/cucurbits/potato) and potential to work alongside biological control methods in glasshouse/ contained crops.

Potential Negative Impacts: Virus recombination leading to new diseases. The specific issues (primary effects) for virus resistance are dealt with in section 6.4.3.

Potential commercialisation within 10 years

Agronomic traits: Virus resistance (Sugar beet, Tomato, Cucurbits, Potato)

The specific issues (primary effects) for virus resistance are dealt with in Gene Flow topic five and above. An additional potential benefit in broad acre crops such as beet, potato or field

[5] Gianessi LP, Silvers CS, Sankula S, Carpenter JE. 2002. Plant biotechnology: current and potential impact for improving pest management in US agriculture: an analysis of 40 case studies. http://www.ncfap.org/40CaseStudies.htm

[6] GM Science Review Website. Halford 2003 http://www.gmsciencedebate.org.uk/topics/forum/0049.htm

[7] GM Science Review Website. Michael 2003 http://www.gmsciencedebate.org.uk/topics/forum/0086.htm

[8] GM Science Review Website. Monsanto 2003 http://www.gmsciencedebate.org.uk/topics/forum/0076.htm

[9] GM Science Review Website. Leaver 2003 http://www.gmsciencedebate.org.uk/topics/forum/0037.htm

tomatoes is in greater choice of rotations and options for crop growth where limited by virus disease at present (eg beet/rhizomania). Virus resistance is seen as potentially beneficial in developing world agriculture, and is the subject of research using locally adapted cultivars of rice (Pinto *et al*. 1999), potato (Murray *et al*. 2002) and cassava.

Fungal tolerance: Wheat and Potato.

Potential Positive Impacts

disease resistance could impact on fungicide spray regimes and provide more robust and long lasting control in the face of evolution of resistant pathogen strains. Commercial development of fungal resistance has lagged behind insect and virus resistance, and has proved technically challenging (Stuiver *et al.* 2001).

Potential negative impacts

Non-target effects are potential impacts of a fungal resistance trait on soil microbes and mycorrhizal fungi during crop growth have been investigated in field trial situations, where no effects were detected (Impact Consortium. 1999, Glandorf *et al.* 1997) however, there is not a major literature in this area. Gene flow giving rise to altered fitness of weeds. is dealt within section 7.3.

Quality/End Use Traits:

- Potato: industrial starch; highly digestible grass and maize
- Nutritionally enhanced vegetables (Tomato)
- Shelf life extended banana
- highly digestible grass and maize
- ‘Designer’ oil and fat molecules in oilseed rape

The direct effects of these traits are likely to be small because agronomic and growth characteristics are not targetted. However, this category covers such a large range of possible products and transformations, that it is hard to make generalisations about environmental impacts. One web contribution has emphasized the perils of any generalisations in this area[10]. Increased feed digestibility of forage grasses and maize might have benefits in terms of productivity and reduced wastage in animal nutrition, extended shelf life banana could have benefits in reduced wastage and transport costs but these potential benefits have yet to be quantified. Transfer of a gene altering major structural components or slowing maturation to wild relatives of a crop that can out-cross might be of ecological significance.

Later commercialisation: traits and target areas in research

The pace of scientific research at a fundamental level has accelerated over recent years. Publication of whole genome sequences for the model plant *Arabidopsis thaliana* (The Arabidopsis Genome Initiative. 2000) and rice (Goff *et al*. 2002), and various microorganisms enables a more complete cataloguing of genes involved in any particular process. Potential application are also being explored both from a classical breeding and biotechnology approaches. Web contributions were received which considered future potential applications across a wide range of targets from crop productivity, yield and quality through to the improvement of human nutrition or the production of industrial and pharmaceutical products[11, 12, 13, 14, 5]. Dunwell’s contribution[15] highlighted the use of IP databases (IP

[10] GM Science Review Website. Tester 2003 http://www.gmsciencedebate.org.uk/topics/forum/0065.htm
[11] GM Science Review Website. Klurfeld 2003 http://www.gmsciencedebate.org.uk/topics/forum/0013.htm
[12] GM Science Review Website. Murphy 2003 http://www.gmsciencedebate.org.uk/topics/forum/0011.htm
[13] GM Science Review Website.Cummings 2003 http://www.gmsciencedebate.org.uk/topics/forum/0031.htm

Database) and field trial applications (Biotechnology and GMO information website) as sources outside the standard literature for understanding what might be in early research. Nonetheless it is impossible to provide definitive answers to the request [16] for clarity on what is possible and will be delivered for the UK citizen. The potential for developing countries was also the subject of web contributions [12, 17].

Seven areas of research which might have environmental impacts, positive or negative, are described below to demonstrate some of the breadth of potential outcomes and issues.

Resistance to abiotic stresses

Plants have evolved a wide array of approaches to respond to abiotic stresses such as frost, heat, drought cold or salt. Research to understand these mechanisms can also proved new options to transfer these traits into crops, as well as providing novel genes for yield improvement. Examples include improvement of salt-tolerance in tomato, although not relevant to UK (Zhang *et al*. 2001), improvement of tolerance of aluminium in soils (Lopez-Bucio *et al*. 2000), improvement of yield from altering photosynthesis or grain starch synthesis (Ku *et al*. 2001, Smidansky *et al*. 2002) Changing the tolerance of crops to abiotic stresses could allow new crops to be grown in the UK, for instance cold-tolerant sunflowers. In addition, predictions of climate changes in the UK (Downing *et al*. 2003) suggest that UK crops will need to become more tolerant of drought in the future.

Potential Positive Impacts

Crops with enhanced tolerance of different stresses enables more flexibility within agriculture and leads to more productivity in problem soils or situations (this may be particulary important in developing countries where poor soils are widespread (Thomson. 2001, Morris. 2003), also relevamt to degraded or desiccated soild in the UK. More attention could then be paid to other objectives such as maintenance of biodiversity.

Potential Negative Impacts

Could enables agriculture to move into new areas that were previously marginal and thus might also be of ecological interest – salt marsh is a key example (although in UK this is very unlikely as the majority of these areas have statutory protection). Adaptive traits such as salt and drought tolerance might also confer on crops, and sexually compatible relatives, an ability to become weeds in these marginal areas

Plants as Renewable sources of industrial feedstocks and energy crops

Cost effective agriculturally-sourced materials to provide renewable supplies of industrial feedstocks such as bulk and speciality chemicals or energy crops are the subject of active research within the EU and elsewhere[18].

Potential Positive Impacts

Replacement of fossil fuel sources of energy and feedstock; new sustainable crops and income for farming communities.

Potential Negative Impacts The potential areas required for growth of such crops could be large which would mean changes to the pattern of agriculture and indirect effects on wildlife and landscape (positive or negative).

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[14] GM Science Review Website. Lamb 2003 http://www.gmsciencedebate.org.uk/topics/forum/0066.htm
[15] GM Science Review Website. Dunwell 2003 http://www.gmsciencedebate.org.uk/topics/forum/0020.htm
[16] GM Science Review Website. Gene Watch UK http://www.gmsciencedebate.org.uk/topics/forum/0008.htm
[17] GM Science Review Website. Harris 2003 http://www.gmsciencedebate.org.uk/topics/forum/0068.htm
[18] Biomatnet , Murphy. 2003 http://www.oit.doe.gov/agricu lture/

Plants as Factories for Pharmaceuticals

As well as being potential production systems for large scale chemicals and feedstocks, plants are also being considered for production of pharmaceutical and other high value proteins. Examples of these applications are the production of antibodies, cytokines and edible vaccines[19, 9, 10, 11]

Potential Positive Impacts

Development of high value speciality crops to improve crop choices and increase farm incomes. Potential to develop rural livelihoods where processing is co-localised. Use of non-animal production systems reduces likelihood of spread of animal disesases; cost effective production of vaccines or antibodies for developing world uses.

Potential Negative Impacts

Containment of the genes and segregation of the speciality crops will need special consideration to keep separate from crops in the food chain. This is a major concern of web contributions [16, 11] as well as being recognised in a number of broad-based science and regulatory reviews (ICSU. 2003), although not without it's critics (Miller, 2003). Impact on wildlife of eating the speciality crop might be harmful, although many would be grown in containment. Potential positive or negative biodiversity effects from introduction of introduction of specialised minor crops for production purposes.

Forest biotechnology

Crops which are particularly slow or difficult to improve through breeding, such as trees, have the potential for improvement through biotechnology. Research is underway to understand and modify the reproductive cycle of trees, to improve tolerance to some herbicides and to change the quality of wood to improve the quality for paper making. (AEBC. 2002, O'Connell *et al.* 2002, Pilate *et al*. 2002, Weizel *et al*. 1995). The environmental impact assessments of GM trees both positive and negative, will raise similar questions to other crops, but there may be special considerations also.

Potential Positive Impacts

GM trees might be a more productive and a renewable source of fuel and forest products, reducing pressures on native forests. Better paper making quality could reduce the environmental impact of this process (Pilate *et al*. 2002).

Potential Negative Impacts

Changing the economics of forestry might encourage extension of managed forestry to previously marginal or ecologically significant areas. Wildlife and amenity aspects of new forest areas are likely to require careful consideration given the scale of land which could potentially be used. Repoductive characteristics of modified trees could also provide important challenges; pollen and seeds are important sources of food for wildlife, and on the other hand, pollen and gene transfer to related species could be an issue. Genetic isolation mechanisms that involve sterility could therefore have adverse effects on wildlife.

Phytoremediation

Using plants to reclaim or clean up pollution is a growing research and commercial area. Plants modified to metabolise, accumulate or tolerate polluted soil, for instance containing arsenic or TNT have been described at a research phase (Dhankar *et al*. 2002, Hannick *et al.* 2002, Biomatnet). Regulatory challenges are being considered (Flechas *et al*. 2003).

[19] GM Science Review Website. Genewatch http://www.gmsciencedebate.org.uk/topics/forum/0009.htm

Potential Positive Impacts
Plants may be able to tackle pollutants that are not susceptible to non-GM remediants. Phytoremediation techniques are particularly pertinent on soils which are contaminated with metals and organic compounds: in the UK this applies to 50% of contaminated soils.
Potential Negative Impacts
These are related to final disposal of the plants grown in contamined soils. (AEBC. 2002). There might also be a concern that efficient cleanup techniques could lessen the regulatory pressure on control of pollution in the first place.

Grasses in agriculture and amenity uses

Grazing, golfing and gardening all have significant environmental impact; many species of grasses are of economic and environmental importance. Application of GM technology to grasses has been reviewed (Wang *et al*. 2001). Targets for modification have included productivity traits for commercial grasslands, herbicide resistance to improve golfcourse management (AEBC. 2002 ref 105,106) and the removal of a major pollen allergen from rygrass (Bhalla *et al. 1999*) . An interesting benefit/risk scenario to explore might be drought-resistant turf grasses – good in terms of reducing water use, but potentially bad if crossing to wild relatives occured.
Potential Positive Impacts
Improved productivity for animal production could make marginal farming more economic; improved management of amenity grass areas such as reduction in mowing or weed control costs, reduction of water use associated with drought tolerance.
Potential Negative Impacts
Highly productive grasses might as an indirect effect encourage pasture improvements and more intensive methods in marginal areas; traits with selective advantages such as drought or salt tolerance might alter grassland ecology if genes introduced into wild grasses. All grasses are wild in the sense that they outcross to the same species; some are very promiscuous and outcross to many other species and genera (Wipff and Fricker, 2000).

Horticultural and minor or exotic crops

Improving the current major crops has been the early target of GM research, however, improving horticultural and minor or marginal crops with special properties (eg flax, lupins and new oilseed crops such as Lunaria) such that they can become a real economic option in a diverse and successful rural economy is a significant research possibility. An interesting example of this is the maintenance of the papaya growing economy in Hawaii and elsewhere in the face of the spread of Papaya ringspot virus was achieved by introduction of virus resistant lines (Ferreira *et al*. 2002). Horticultural crops such as tomato, banana, strawberry and peppers have a high demand for quality in the market place. Modification of ripening characteristics has been widely studied (AEBC. 2002, James. 2003). Modification of fruit trees could be a route to preserve local varities with specific heirloom quality traits while bringing improvement to specific agronomic weaknesses limiting their current potential[20].

[20] GM Science Review Website. James 2003 http://www.gmsciencedebate.org.uk/topics/forum/0029.htm

Box 6.4 Case study of Potato Cyst Nematode (PCN) research and benefits

Potato cyst nematode (PCN) in the UK is a very serious problem occurring in 64% of potato fields in England and Wales and causing annual yield losses of approximately £43 million between 1990-1995. Resistance to nematodes is a very strong example of the clear benefits of a GM technology for the UK.

- The current control of PCN in the UK is based on oxime carbamates/carbamates that are highly toxic to most animals. One (Temik or aldicarb) will be withdrawn by the EU in a few years. The future of the other main chemical (oxamyl/vydate) is uncertain. Aldicarb is very water-soluble, becomes stable in groundwater and kills soil animals e.g. earthworm populations and have the potential to kill birds if not used correctly. There is even more concern about nematicides in a developing world context.

- A GM approach developed by the University of Leeds involves a plant gene naturally expressed in rice seed. Similar proteins are found in maize seed, egg white and saliva. These proteins inhibit cysteine proteinases and they are termed cystatins. They interfere with the nematode's ability to digest its dietary protein.

- Several field trials in the UK have established that the cystatins provide a useful level of resistance when expressed in potato (Urwin *et al,* 2001), The resistance has recently been shown to stack with natural partial resistance and obtain full control of PCN (Urwin *et al.* 2003)**.** Preliminary biosafety studies indicate that soil microbes, earthworms, aphids and leafhoppers are not affected by plants expressing cystatins.

- The technology has potential against many nematodes worldwide. It is donated for many developing world applications. It could provide benign control of nematodes that reduce current yields of subsistence growers and reduce exposure of agricultural workers to hazardous compounds

6.6.4 Is there General Scientific Agreement?

There is most scientific agreement in relation to the possibilities of particular technological goals being achievable at an experimental scale. The pace of scientific developments is such that many things are possible, and laboratory proof of principle has been achieved for a great many traits.

This broad scientific agreement on possibilities breaks down when possibilities are turned into products.

Firstly, the likelihood, timing and scale of a particular product being developed in the UK is subject to a wide variety of views as to likelihood, timing and desirability [21,16, 11] .There is an enormous gap between a proof of principle which might be written up in a patent application or publication in a refereed journal and a product being placed on the market. The nature and pace of introduction of GM plants into UK agriculture and horticulture is therefore hard to predict. This aspect of uncertainty is covered in the study of economic impact of the Strategy Unit. The most far off products have the most uncertainty as to likelihood of commercialisation. The pace of development of UK-specific expertise in both developing crops for specific environmental applications and testing in real life is not rapid at present so much of the progress and direction will be from elsewhere with the UK reacting to developments and being a secondary market.

Secondly, there is less agreement on the environmental impact of potential future products. Hazard, likelihood and benefit are all subject to argument, both in terms of significance in relation to any regulatory system and in terms of the appropriate tests to carry out for regulatory clearance. There are no international bodies analogous to the Codex alimentarius Commission for food regulation (Miller. 2003).

Hazard: what are the hazards, how broad to cast the net in relation to indirect effects; how much environmental value to place on weeds and pests which are part of an ecological food web. What tests and trials should be used to monitor and assess these effects? How can the tests be made non-discriminatory between technological approaches?

Likelihood: What meaningful tests can be adopted when recognising that proving zero likelihood is not possible as a regulatory or scientific goal

For the products in catagories A and B, the key scientific uncertainties are the extent to which experience elsewhere in the world is a good guide to the environmental impact in the UK. Subsidiary issues where views differ is the extent to which the environmental impact of crops which are imported to the UK should be considered at all (for instance in considering insect-resistant maize where the targeted pests are not found in the UK), and the question of how EU regulations impact decisions in developing countries (Morris. 2003, Miller. 2003). A case-by-case evaluation still seems to be the most robust approach in considering each potential product.

6.6.5 Are the Issues Unique to GM?

Not in most cases. All the targets listed are largely independent of the technology approach and are addressed currently through conventional approaches to improvement (even for pharmacetical production, the environmental impact of current production systems is a regulated aspect of the manufacturing process). What is different is the potential of significant step change outcomes which could move the trait/crop properties "forward" in a dramatic way. Another aspect of this is that a GM trait would be visible to the regulatory regime in a way that a conventionally bred salt tolerant variety or an exotic introduction (eg new interspecific willow or grass hybrid) may not be. In such a case, the issues would be addressed in the regulatory review process (see chapter 3).

6.6.6 Are there gaps in our knowledge or scientific uncertainties, and are these important?

One web contribution specifically lists uncertainties and gaps[21] after assessment of the literature in 2000. This study identified Controversies (questions not answered unequivocally) and or Gaps (questions not receiving adequate attention) in relation to the following topics.

- Effects on biodiversity
- Effects on sustainability

[21] GM Science Review Website Greenpeace http://www.gmsciencedebate.org.uk/topics/forum/0026.htm http://www.gmsciencedebate.org.uk/topics/forum/0083.htm

- Effects between neighbouring agro-ecosystems +/- GM crops
- Predictability of environmental effects

Other more detailed science questions have been suggested during the review process, and have considerable overlap with this list:

- Agro-ecological data and models of farming systems as baselines for assessing potential changes and impacts.

- Indirect and non-target effects of pest, disease and abiotic stress resistance traits: methodology and simple, robust assays for early stage evaluation.

- Soil ecology and function data and models as baselines for assessing potential changes and impacts

- Scale up: understanding of impact of gene flow and other effects from commercial-scale crop use particularly when applied to crops beyond the well-studied current crops. Use of this information in development of robust testing approaches in research and development.

- Impact of introduced genes upon ecological fitness of wild species.

6.6.7 Likely Future Developments

This topic area is concerned entirely with future developments. Suffice it to say that it is likely that the pace of scientific developments will continue to be rapid, generating more demonstrations of principle both of how plants work and of ways they could be changed for the benefit of humans and the environment either through genetic modification or a range of "smart" breeding approaches enhancing current tools and methods. The regulatory system will need to be able to assess the impacts of combinations of gene effects and also traits providing more profound changes to crop biology.

6.6.8 Where there is Important Scientific Uncertainty, what is the Way Forward?

Science

The scientific opportunities to research the gap areas listed above are quite open ended and challenging, and not really unique or specific to GM.. On the one hand case-by-case review is recommended for particular environments, and on the other general background data, models, methods, protocols and approaches are required to underpin a science-based international regulatory regime. And many of these factors are simply not available for environmental assessment, unlike food and animal feed safety

Baseline data and models of agricultural ecosystems would help in policy and decision making within the UK agri-environment context.

Simple robust tests of relevance to environmental impact would be useful in research and commercial practice

Regulation

The experience from centuries of conventional agriculture and the existing science base allows the regulatory system to foresee some of the general principles to be considered in assessing environmental impacts of new GM crop developments. However, science has been developing rapidly over the last century, and correspondingly, the ability for new approaches and methodologies to understand environmental impact at a deeper level has brought the opportunity to re-evaluate understanding and accepted practices.

Nevertheless, the key uncertainties around environmental impact are likely to beprincipally indirect. Economic factors (at micro and macro level) will drive decisions at farm and regional level and hence lead to potential indirect effects. Changes in EU agricultural regimes are likely to be far more significant causes of such indirect effects.

6.7 CHANGES IN AGRICULTURAL PRACTICE

Might GM crops change agricultural practice in the UK? If so, what might be the likely consequences?

6.7.1 Summary

It is widely acknowledged that modern (non-GM) agriculture has already had significant negative impacts on biodiversity and the wider environment in the UK. Large changes over the last century, including recent decades, in the way that farmland is managed have resulted in a decline in both on- and off-farm plant, invertebrate and bird abundance and diversity. The species that have been hardest hit are specialists of the arable environment, which thrive in very particular habitats, though intensification has made some commonplace species much rarer.

GM technology might have the potential to increase biodiversity and reduce some environmental impacts of farming, such as pesticide applications although as yet these benefits have not been demonstrated in the UK. Alternatively it may intensify agriculture with detrimental effects on biodiversity.

It is impossible to state categorically what will happen to agricultural practices following the adoption of GM crops in the UK. Overall, the consequences will depend on the nature of each individual product and what farmers, the public, and policy makers decide. Due to this uncertainty, many of the potential changes it could bring about in agriculture are speculative. There is a major need for policy makers to understand how these factors are likely to interface with the new technologies, because they will need to predict outcomes from the environment if targets are to be delivered.

If GM crops are grown in the UK, the farming system most likely to be affected by the technology will be the sector that benefits the most economically. At present it is thought that this is likely to be arable and mixed lowland farming, because they are currently the most productive and potentially profitable sectors of agriculture.

GM technology might have the potential to increase biodiversity and reduce some environmental impacts of farming, such as pesticide applications. It may intensify agriculture, with possible detrimental effects on biodiversity. Alternatively, this intensification may have the effect of reducing the amount of land dedicated to crops, leaving the rest of the land for other purposes, such as nature conservation.

6.7.2 Background

Almost every habitat in the United Kingdom is affected by farming. Of the 24 million hectares in the UK, 19% are crops and bare fallow, 48% grass and rough grazing, 3% other farm use, 11% forest and woodland, and 18% urban land and that used for transport, recreation and non-agricultural use (e.g. sand dunes, inland water, grouse moors).

Farmland is therefore a very important habitat for wildlife. Any changes in agricultural practice in the UK, whether GM or non-GM (crops and varieties grown, rotations, intensity of agriculture, herbicide and pesticide applications, cropping patterns, number and nature of field operations) will have effects on the wildlife within and surrounding that habitat.

Drainage and increased fertilizer use have led to losses of floristically-rich meadows and an increase in grass monocultures, overgrazing of uplands by sheep and deer has reduced species diversity, herbicides have reduced diversity of flowering plants in arable fields and led to some formerly abundant arable weeds now being classified as extremely rare (Wilson and King, 2003). Farmland birds have particularly suffered: the populations of nine species fell by more than a half between 1970-1995 (Pain and Pienkowski, 1997; UK Biodiversity Steering Group, 1995, 1998, 1999). This was discussed at the Royal Society meeting[1].

This is the backdrop for further technological change in agriculture – whether it be GM or non-GM. Farming has always shaped rural biodiversity and the countryside, and has already had far-reaching and fundamental effects (Jenkins, 2002; Pretty, 2002; Robinson and Sutherland, 2002). Some 25 of the 200 species of British arable plants are now nationally scarce, and a further 24 are of conservation concern (Johnson, 2000). Farmland bird diversity and biomass has fallen, with the populations of at least 13 species now considered so low that they need special protection (Siriwardena *et al.* 1998). The key question is: would the adoption of GM crops (and the crop management choices they provide) increase, slow down, or reverse the rate and direction of change while contributing to improvements in farm productivity and efficiency?

6.7.3 Range of views

The main purpose of the first generation of GM crops is to give farmers more, easier and cheaper options for control of pests, diseases and weeds. Giving greater control could mean either benefit or harm to biodiversity, depending on the farmers' objectives, and market and policy drivers.

It may be possible to manage GM crops in such a way that some weeds and the insects associated with them are left for birds but the evidence for this is at present limited (Dewar *et al.* 2000); such methods may have associated crop yield losses. But it is equally possible that GM HT or insect resistant crops may produce even more weed-free and invertebrate-free fields. If GM crops are introduced to the farms that already have very low residual weed numbers in their fields, it will have little impact on bird populations. However, if those remaining farms with weed-rich fields or field margins grow GM crops, they may become weed-free and pest free, thus decreasing the reservoirs of food and cause bird numbers to drop even further (Watkinson *et al.* 2000). It is because some of the current GM HT crops currently under consideration for commercial approval in the UK, (e.g. fodder beet), are known currently to be weed-rich compared with others such as autumn-sown wheat that wildlife conservationists have concerns about their use. (See section 6.5 for detailed discussion on new weed control strategies offered by GM HT).

While some GM technologies may lead to reduced agrochemical use, benefiting biodiversity and water quality, others could result in greater use of agrochemicals (ERS-USDA, 1999; Dewar *et al.* 2000; Elmore *et al.* 2001; Huang *et al.*2002; Pray *et al.* 2002). There may be an increased uptake of environmentally beneficial farm methods, such as zero or minimum

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[1] Royal Society Meeting, Watkinson, Vickery, http://www.gmsciencedebate.org.uk/meetings/pdf/110203-transcript.pdf

tillage, which though requiring more herbicide, will lead to improved soil carbon storage and reduced run-off pollution (Renwick *et al.* 2002).

This section is based on an analysis of the potential changes to three UK agricultural sectors. The farming system most likely to be affected by GM technology is likely to be the one that benefits most economically (Countryside Agency, 2002). All traits are considered in a post-commercial approval scenario, which will differ in their timing and impact from crop to crop.

Arable and Mixed Lowlands

These systems are likely to show the greatest changes, largely because they are the most productive and potentially-profitable sectors of farming, and so would be the target of commercial enterprises developing GM crops. Over the first few years after commercial approval[2], the following changes could occur in farming systems:

- Herbicide-tolerant (HT) oil seed rape and fodder beet would come into common use;

- Non-GM alternative crops, as import substitutes, could also become more common, with soya, lupins and beans/peas replacing GM products from the USA and Latin America. Alternatively these protein crops could be imported from other non-GM growing countries.

- Trees with altered lignin/ cellulose ratios for paper production.

- High-value pharmaceutical and nutraceutical crops could be grown, but only on a relatively small scale.

- Fungal-tolerant potatoes and wheat could come into commercial use, thus reducing the need for fungicide applications.

- GM cereals could be more common, particularly those with HT and insect resistant traits. Their use would be greater if they have been shown to reduce the use and impacts of herbicides and insecticides, and if reduced-tillage systems become more popular, thus leading to benefits for the environment and for lower farm costs.

- High nitrogen-use efficiency in wheat and potatoes (currently far from development as a commercial possibility) could reduce the need for nitrogen fertilizers, so benefiting the environment through reduced nitrate leaching and nitrous oxide emissions, as well as reducing farm costs.

- Increased cultivation of insect and disease resistant vegetables and flowers is possible, thus reducing some pesticide use.

Crop rotations might become more diverse, as GM traits could increase the economic value of some crops (e.g. oats and legumes) and might therefore increase the likelihood of farmers cultivating them in rotations although lack of markets might constrain this likelihood. Alternatively if some GM crops currently used as break crops in rotations, such as oil seed rape, have substantial yield and economic advantages, then they may become even more

[2] Refers to commercial approval, should this be granted. Approval is very case specific and each trait differs in timing, given its current state of development. See chapter 6.6 for further details.

common as break crops in cereal rotations which could lead to a less diverse landscape, with the majority of farmers opting for them. Another possible scenario is that resistance to biotic stresses and better weed control via HT traits would mean no need for break crops – so continuous cereal cropping could be a result.

The consequences of such adoption of GM technologies over the decade after commercial approval may include the emergence of some new agronomic problems, such as HT volunteers in crop rotations and the emergence of secondary pests and weeds. UK farmers may become more globally competitive, through lower costs for inputs; reduced insecticide use, and reduced water pollution; and increased uptake of zero or minimum tillage systems, with some benefits for soil moisture retention and reduced soil erosion.

Lowland dairy and Beef Systems

On current estimates, these systems are likely to show an intermediate level of change with the projected adoption of GM crops. The most likely candidate for early commercial cultivation is HT maize. It is unlikely that more productive forage grasses will be approved for release in the UK in the near future.

It is not clear what would occur as a result of widespread adoption of HT fodder maize. At present maize fields are almost entirely weed free because of atrazine use. Atrazine has been banned from most uses in the UK because of its effects on human health and use on fodder maize is one of its few legal uses in the UK. It remains to be seen whether the use of HT maize would offer new opportunities to control weeds, making the fields more wildlife friendly.

Of greater concern, however, would be the introduction of new forage grasses that could be substituted for traditional or `unimproved’ grasslands and meadows. Where they would substitute for existing intensive grasslands, then the marginal effects on landscape would be small. But if farmers are tempted, or permitted, to use more productive GM varieties to spread further the process of intensification, then there will be additional biodiversity and landscape losses. As there are very few remaining unimproved meadows in the UK, these may require further protection (Robinson and Sutherland, 2002), if not already protected as SSSIs[3]. Some GM forage grasses may, however, reduce the likelihood of farmers de-intensifying their grassland systems, or adopting new management intensive rotational grazing, both of which have substantial benefits for landscape diversity and farm incomes. However, given the current climate of GM regulation it is unlikely that more productive forage grasses will be approved for release in the UK, because of the concern that the GM trait would be transferred to the large number of wild relatives. Traditional breeding approaches to this target continue in the meantime.

Given market acceptance, lowland livestock systems at the aggregate level could become more diverse, as the number of profitable options for farmers would increase, including GM oats and legumes, more productive grasses, HT and/or insect resistant fodder maize, and grasses with reduced nitrogen requirements. Once again, though, a particularly economically beneficial GM technology could come into widespread use very rapidly (as is the case for many other agricultural technologies).

[3] Site of Special Scientific Interest

Upland Livestock and Permanent Pasture

These landscapes are likely to see much less change than arable and lowland livestock systems after commercial approval of GM crops. More productive grasses could lead to greater intensification of grazing, leading to more animals per hectare. The same could happen if GM acid- and cold-tolerant grasses were developed, so permitting farmers to expand the current limits of intensive production to higher altitudes and latitudes, possibly leading to losses in biodiversity.

6.7.4 Is there general scientific agreement?

Some GM crops could speed the process of agricultural intensification, so contributing to further losses of farmland biodiversity and valued landscape features, if applied broadly. But GM products could also result in a more diverse landscape, with the adoption of niche crops and new high-value options, such as energy crops (Nuffield Council on Bioethics, 1999; House of Lords, 1999; Royal Society *et al.* 2000; Pretty, 2001), although in the short term this is unlikely to happen because GM crops currently under consideration would mostly replace non-GM varieties.

The extent to which a new agricultural technology alone can bring about significant change is uncertain and will probably depend on the economic, agronomic and other advantages that the new technology delivers to farmers. What is not in doubt is that agricultural policy subsidies and support also play a huge role in defining the possibilities of uptake of new technologies. Recent incentives for maximising agricultural production provided by the Common Agricultural Policy were the backdrop to the removal of hedgerows from the countryside (a change not dependent on any new technology) but also a massive switch from spring-sown to autumn-sown cereals (only possible through the availability of new herbicides and new conventionally-bred cereal varieties). Thus the uptake of any GM crop will depend critically on its advantages to the farmer as well as the policy background.

A further important factor in the uptake of GM technology by farmers will be their acceptability to the consumer. Consumer choice between GM and non-GM produce will override any agronomic advantage or disadvantage that GM crops may or may not have for the farmer.

6.7.5 Is the issue unique to GM?

Yes, in the sense that GM crops offer new agronomic possibilities, such as the widespread use of herbicide tolerances, and the adaptation of crops to difficult environments. However, it is widely acknowledged that modern (non-GM) agriculture has adopted new technology and processes to improve productivity and competitiveness from many sources and that this has had significant negative impacts on biodiversity and the wider environment in the UK and that these are greater than in many other parts of Europe (Conway and Pretty, 1991; Campbell *et al.* 1997; Pretty *et al.* 2000; EA, 2002; Robinson and Sutherland, 2002). Large changes over the last century, including recent decades, in the way that farmland is managed have resulted in a decline in both on- and off-farm plant, invertebrate and bird abundance and diversity. The species that have been hardest hit are specialists, which thrive in very particular habitats, though intensification has made some commonplace species much rarer.

Modern conventional agriculture has already produced a landscape in which many fields have very few invertebrates and very few weeds, providing little food for other types of wildlife, especially birds. In the course of the 20th century there was a 95% decline in the number of weed seeds in the environment. From 1900 – 1930 there was a range of plants, many of them annuals, which were fairly widespread. By the 1960s some had become very rare, such as *Agrostemma githago* (corncockle). This was formerly widespread, but has since declined to extinction. All those now seen in the countryside have come from wild flower seed mixes. Other plants that have dwindled in number or disappeared include the cornflower, corn cleavers, red hemp nettle and pheasant's-eye. All are wildflowers associated with arable farming (Robinson and Sutherland, 2002).

Thus, one important environmental issue surrounding GM crops, particularly GM HT crops, is whether they might make a bad situation for biodiversity even worse. There are many other changes in agricultural practice, which over the same timescale could also have deleterious effects on biodiversity, and many of these are currently subject to less scrutiny than GM crops. Examples would include the future development of conventionally bred HT crops, the expansion of biomass crops on a large scale in the UK countryside and the continuation of land drainage practices which affect SSSIs and the wider countryside.

This issue is therefore not unique to GM crops, but part of the wider consideration of agriculture, environment and the rural economy, which is at the heart of the debate over review and reform of the Common Agricultural Policy

6.7.6 Are there important gaps in out knowledge or scientific uncertainties and are these important?

There are many uncertainties in the topics covered here, and necessarily so because of the huge uncertainties in this area. Some of these gaps are scientific but many are social or economic. The complex ecological interactions between all the components of agro-ecosystems are not yet fully understood, including those related to the effects of schemes designed to produce benefits for the countryside and biodiversity (e.g. Countryside Stewardship). Therefore, it is not possible to predict with certainty all the consequences of ecosystem change on biodiversity brought about by small or large changes in agricultural technologies.

There is a major need for policy makers to understand how these factors are likely to interface with the new technologies, because they will need to predict outcomes from the environment if targets are to be delivered.

6.7.7 Likely future developments

More laboratory and field experiments, combined with better ecological knowledge of all the side-effects of farming, will increase scientific knowledge of the potential impacts of a wide range of GM crops on all possible crop-environment combinations. However, it is important to note that the effects on agriculture are more likely to be from political, economic and social change than growth of scientific knowledge.

With biotechnology, farmers' practices could get more complicated, with separation distances, volunteer management, refugia (see box 6.3), etc. Because of this environmental management could become more difficult for farmers.

6.7.8 Where there is important scientific uncertainty, what is the way forward?

Scientific uncertainty centres on the effects of GM crops on specific agricultural environments, particularly with respect to the effects of farmers' practices. If GM crops are given commercial approval then their impact on the environment, either positive or negative may be influenced considerably by any guidelines for management of the crop (or other areas), which accompany them. For example, if the provision of insect refugia were seen to be an important concomitant measure to accompany insect-resistant crops then the extent to which farmers complied with such guidelines would influence their benefits. This could act in either direction – those farmers acting with particular care could deliver more than the expected benefits and any falling short of full implementation could reduce any such benefits. The confidence with which it was felt that guidelines would be implemented by farmers as a whole would influence the extent to which regulating authorities would consider guidelines to be voluntary measures or whether they should be made a condition of commercial approval. There is a clear need for more research in these areas to monitor uptake and application of new technologies in general and GM crops in particular.

6.8 LIMITATIONS OF SCIENCE

Is the science available to predict the environmental impact of GM plants?

6.8.1 Summary

The main approaches for determining and predicting the environmental consequences of GM crops are: comparisons with non-GM crops, experience with comparable traits, experiments, field experience of GM crops and ecological modelling. A combination of comparative, experimental, observational and theoretical approaches is typically used to consider the implications of a given trait.

Most of the environmental issues raised by traits resulting from currently developed GM crops do not differ qualitatively from those associated with conventional crops.

Models are important for placing any anticipated changes in context, and are important for scaling-up from experiments to landscape-level impacts.

A major conclusion of this review in relation to currently available GM crops is that the issue of greatest environmental concern is the potential consequence of changes in herbicide management of GM HT crops which might reduce weed populations and hence impact of seed eating birds and other groups. The underlying ecology of the weeds is reasonably well understood and the herbicides involved are well studied. The current farm-scale evaluations have been devised to examine this very issue of the consequences of management of GM HT crops upon wildlife and should provide an excellent basis for understanding the consequences. Thus should then be one of the best understood potential changes in the agricultural landscape.

The environmental effects and implications of various agricultural weed-control strategies have been observed over the last century and experimental work has analysed the impact of various strategies. The FSEs will show any environmental implications specific to GM herbicide tolerant crops. If the results suggest that there may be implications from the GM HT crops, then it is important to understand the groups of farmers who are likely to take up the technology if we are to predict the consequences on a landscape scale. Fields differ greatly in weed density and a critical issue is whether the small proportion of fields with high weed density are likely or unlikely to be planted with herbicide tolerant crops.

6.8.2 Background

There is a range of possible environmental concerns related to the use of GM crops, and it is essential to evaluate the possible impacts of these. This requires predicting the ecological response to novel environmental conditions. In this section we review the methods that are adopted and the strengths and limitations of each.

In order to predict the environmental impacts of GM crops we first need to develop testable hypotheses about the kinds of impacts that might occur. It is logically impossible to predict and/or quantify the impact of an unknown risk.
Over the last 20-30 years risk assessment frameworks for genetically modified organisms have gradually been developed and refined by the scientific community and regulatory

authorities. These frameworks are based on, among other things, our understanding of how plants interact with the physical environment and with other organisms, how transgenes are likely to affect these interactions, the behaviour of transgenes within the host genome and their ability to move into other genomes, and the way in which agricultural management practices affect the wildlife and natural resources in and around farmland. For example, the UK regulations on GMO release require applicants to answer a series of detailed questions that cover direct impacts of the crop itself on the environment, the potential for gene flow to lead to ecological disruption, and indirect effects of the way a GM crop is managed by farmers.

Most scientists today are confident that we have a good understanding of the main types of environmental risk that could arise from the release of GM crops (even though we may lack the data or modelling capability to adequately quantify all of these risks). However, some commentators have argued that since genetic modification is a relatively new technology, there may be environmental (or other) risks that our knowledge of genetics, ecology or ecotoxicity does not yet enable us to predict. For example, scientists in the 1940s lacked the knowledge to predict that the insecticide DDT would reduce the thickness of the eggshells of peregrine falcons. It is important to acknowledge that we may still not be asking all of the right questions, let alone have the science to provide answers to them.

The results described and discussed here are restricted to the impact of GM crops on the UK environment.

6.8.3 Range of views and quality of evidence

There are five main approaches used in predicting the environmental impacts of GM crops. In practice it is usual to use a combination of a number of these methods.

This section does not consider the issue of gene flow, which is the subject of Chapter 7, while Chapter 5 considers the safety of GM food and feed.

Comparisons with non GM crops

This entails comparing the GM crop with existing crops to determine the differences. Thus if there are crops that are widely used and accepted by society, then it is clearly unreasonable for regulatory systems to question those characters that are shared by both the GM and conventional crops. Risk assessment must concentrate upon those traits that differ between GM and conventional crops. This may lead to three possible outcomes

(i) The GM crop may not differ in expected environmental impact from existing crops. For example, where the crop management will not differ significantly from current practices and it can be demonstrated that the transgenic phenotype is unlikely to change the interactions with other organisms in the field. In these cases it is clear that the ecological impacts will be insignificant.

(ii) The GM crop may be similar to conventional crops except for certain specific traits. It is then necessary to consider the implications of these traits. If the crop contains several transgenic traits then the comparison will need to consider the interaction between the traits.

(iii) The GM crop has no equivalent crop that is comparable. This would clearly involve a challenging and detailed assessment. We do not believe this applies to any of the environmental issues that we discuss in this section however it may be possible in the future as our ability to make more radical transformations increases.

A crop or product is expected to differ from its conventional counterpart only in the transgenic trait which it has been engineered to express, therefore risk assessments concentrate upon the impacts of the trait of interest. This approach has been criticised by some (e.g. Millstone *et al.* 1999) especially where there may be some uncertainty as to the phenotypic consequences of changes in the genotype. For example *Bt* maize was found to contain elevated levels of lignin (Saxena & Stotzky 2001) and Roundup Ready soyabean was observed in the field to have higher levels of stem splitting in hot weather – perhaps due to higher lignin levels (Gertz *et al.* 1999). The majority of unpredicted significant changes in phenotype, particularly if detrimental to crop morphology or development, would be detected during agronomic field trials at the research and development stage.

Comparison with non GM crops is best considered as the preliminary stage to guide risk assessment and to be followed by some of the following approaches. The amount and type of data required to carry out a risk assessment on a particular GM crop will depend largely on the crop species, the nature of the transgene(s) and the extent of prior experience with other similar transgenic crops.

Experience with comparable situations

Although a given trait may be novel, experience from comparable situations may provide useful insights. For example, the experience of using more efficient herbicides in conventional agriculture can be used to predict the consequences of the use of GM herbicide tolerant crops. As another example, the experience of the introduction of conventional novel crops and varieties with enhanced pest resistance can be used to give insights into the likelihood that there will be problems with toxicity to wildlife of GM crops. As a third example, the behaviour of conventional crop varieties that have escaped from cultivation can be used to assess the likelihood that GM crops with traits that are unlikely to enhance fitness outside cropped habitats will become invasive. See section 6.2.

An important question is what is considered to be comparable. For example, the current programme of Farm Scale Evaluations (FSEs) is assessing the impacts of specific crops and herbicides on biodiversity in and around fields, for example GM maize resistant to the herbicide glufosinate ammonium. At some time in the future, it is likely that other combinations of GM HT crops and herbicides will be considered for commercial release (for example, glyphosate-tolerant maize) and in this situation regulatory authorities might need to assess whether the impacts of the glyphosate and glufosinate could be considered comparable or whether further large-scale field trials would be required for an adequate risk assessment.

Experiments

Experiments can be a very powerful means to predict ecological responses to changed conditions and can be carried out in the laboratory and in greenhouses (under contained conditions) and in the field (deliberate release). Laboratory experiments are the usual initial stage before considering field experiments of GM crops. They are easier to carry out as they avoid the spatial and temporal variability associated with field studies. Containment is also much easier for laboratory experiments.

Well-designed scientific experiments allow the manipulation of variables under reasonably controlled conditions. Laboratory and greenhouse studies offer the possibility of close control over environmental conditions and enable detailed comparisons between different crops and traits. However, it may be difficult or impossible to accurately replicate field conditions and therefore predict the actual impacts on biodiversity.

Field experiments may be carried out at a variety of scales: in general larger plot size combined with higher numbers of replications will enable a wider range of environmental conditions (including both temporal and spatial variation) to be studied and therefore give more accurate predictions of impacts. However, including too many environmental variables in field experiments may mean that it is difficult to separate out the impacts of the transgenic trait(s) under study. Therefore, the design of field experiments usually involves a compromise between the degree of accuracy required and the ability to control environmental variables (e.g. split field or paired field plots in FSEs) and also the cost of field research – a major consideration. Additionally, field research involves a deliberate release of GM crops into the environment and as such may involve greater risks of environmental impacts such as gene flow from trial sites (depending on the species under study). Therefore a decision to proceed from contained to field research must be backed up by evidence from laboratory studies to show that risks of invasiveness or gene flow are acceptably low.

Field experiments can be an excellent means for examining likely responses but can be expensive and contentious. They are strongest when they replicate realistically conditions in the field. For example, for insect-resistant crops, most of the experimental research on impacts of crop-produced toxins on non-target organisms has been carried out in the laboratory. Research at the field-scale has been very limited. Lab research can be useful in identifying potential hazards or impacts but these can only be tested reliably by agronomically realistic field-scale experiments. Once such case was the Monarch butterfly (Losey *et al.* 1999, Hansen & Obrycki, 2000) which suggested that pollen from a particular line of *Bt* maize with high expression level could increase mortality in Monarch butterfly larvae. Laboratory studies do not necessarily mean a real risk arises in the field. Later research indicated that Monarch migration and *Bt* pollen show does not coincide; that pollen does not travel far (90% falls in the first 5 metres); that larvae on milkweed are not adversely affected by *Bt* pollen; and that most milkweed tends not to be found close to maize fields. (Hellmich *et al.* 2001; Oberhauser *et al.* 2001; Pleasants *et al.* 2001; Sears *et al.* 2001; Stanley-Horn *et al.* 2001; Zangerl *et al.* 2001). See Sction 6.3 for a more extensive discussion of this issue.

Experiments can examine components of fitness (e.g. survival and fecundity) and see how these are affected by management and field conditions (Parker & Kareiva 1996). Thus, after field experience showed that conventional rape plants only persisted ephemerally outside agricultural land, experiments were used to determine whether the GM plants were more invasive (see section 6.2). The PROSAMO experiments showed that a selection of GM herbicide-tolerant crop plants were never more invasive than their conventional counterparts in any of eight experimental treatments at any of 12 locations (Crawley *et al.* 2001).

If experiments do identify environmental differences resulting from GM crops compared to conventional crops, then models are required to predict their long-term and large-scale implications because experiments usually only last one or two years. For example models of the type outlined by Watkinson *et al.* (2000) can be used to predict long-term changes in weed and bird populations rather that the response over just one or two years. The current farm scale evaluations should provide convincing evidence on the implications of herbicide tolerant crops for weed and invertebrate population ecology. However they are too small to assess the impacts on birds (Chamberlain *et al.* 2002). The results will need to be incorporated into population models in order to predict the long-term changes rather than the response over one or two years, to predict the changes over landscape scales and to attempt to predict the implications for wide-ranging taxa such as birds (Watkinson *et al.* 2000).

Field experience of GM crops

Examining the actual consequences of growing GM crops in the field under commercial conditions is a useful tool in risk assessment. The approach may be either to examine the experience from growing the same or similar varieties elsewhere (e.g. North America) or monitor the consequences of GM crops if they are introduced into the UK.

Examining the consequences of the same or similar varieties grown elsewhere has the advantage that the consequences of realistic, and sometimes large-scale, planting can be assessed before the crop is actually introduced to the UK. Although likely to produce useful insights, there is an issue that agricultural ecosystems often differ between countries, so there is a possibility that responses may differ. For example, rotations in North America are often less diverse than in the UK, so the ecological impacts of GM HT crops may be exacerbated there; on the other hand, wildlife in the UK is more reliant on the cropped environment and so may be more severely affected by increases in herbicide efficiency than in North America. EU risk assessment requires that field trials must be conducted in European environments or that adequate bridging studies be carried out other wise.

Comparison with experience elsewhere is obviously a very useful approach (e.g. Owen 2000) but there has been surprisingly little work studying existing commercially-grown GM crops, probably because farmland wildlife does not have the same significance in the countries where GM crops are currently commercialised. If there were dramatic affects then it seems probable that these would have been detected.

If GM crops are introduced into the UK, then monitoring any impact on biodiversity within farmland and associated habitats will be important in confirming the validity of the risk assessments but difficult. Although the current UK bird population monitoring organised by the British Trust for Ornithology is perhaps the best in the world, it would have difficulties detecting small persistent changes from annual variability, especially due to weather. Furthermore, it would not be straightforward to determine the impact of GM crops within the existing monitoring as it would presumably be necessary to question the farmer as to which crops are GM while much of the current surveying, including identifying crops, is done from public footpaths. Furthermore, if the critical change is the winter food supply then it will be difficult to relate changes in breeding population to changes in farming practice over a wider area. Despite intensive research on farmland birds it has been very difficult to determine the mechanisms behind the decline as a suite of changes has occurred simultaneously (Robinson and Sutherland 2002). In the future there are also likely to be suites of changes, so that determining any causal role for GM crops is likely to be difficult unless there is a detailed programme to examine this specifically.

Ecological modelling

Models are a standard methodology that underpin much of science. A mathematical description of the world can provide a rigorous understanding and is essential for quantitative predictions (with certain limitations – see later). Population models use a series of equations to describe the ecological interactions. The most basic model comprises understanding the birth, death, immigration and emigration rates and how these are affected by population density. It is then possible to predict the expected population size.

Models have the considerable advantage that they can make use of pre-existing information. For instance pre existing models and existing field studies can be employed to predict changes in management with GM HT crops by incorporating the possible changes in plant survival and could consider possible changes in seed survival (for example as a result of changes in tilling or subsoiling operations).

Ecological modelling is usually explanatory and confirmative rather than predictive but is increasing in its ability to make predictions. For example, for the bitterling (a freshwater fish), Smith *et al.* (2000) quantified how the birth rate depended upon the number and species of mussels in which they bred, while the death rate of the young depended upon an interaction between the density within nursery habitat and the density of predatory perch. It was then possible to predict the density of bitterling within a range of lakes given the extent of the nursery habitat, mussel density and perch abundance and tests showed that these predictions fitted reasonably well (Smith *et al.* 2000).

By understanding the underlying processes it is possible to predict the responses to novel conditions. Stephens *et al.* (2002a) used behavioural data on alpine marmots to predict the underlying population ecology and by testing the output of these models showed that the models appeared to perform well. They could then be used to predict the response to novel conditions such as changes in exploitation (Stephens *et al.* 2002b). Stillman *et al.* (2000) predicted the mortality of oystercatchers in relation to their density by quantifying the fundamental components of their ecology and behaviour. This model provided a good fit to the actual change in population density.

Muir and Howard (2001) evaluated the likely ability of transgenic fish to persist by measuring differences in components of fitness (juvenile and adult viability, age at sexual maturity, female fecundity, male fertility, and mating success) and then incorporating these into a mathematical model that integrates them into a single prediction of risk. This approach has not yet been tested on other organisms.

The ability to create predictive models will vary between subjects. For weed populations the data and understanding are good. The link to bird populations is better in the winter when feeding upon seed that in the summer when most feed on arthropods. There is the theoretical framework for studying the ability of genes to spread in the population but much depends upon determining the selection pressure. The current knowledge is insufficient to model the impacts of insect/ disease resistant crops on non target species.

Limitations to predictions

Predictions are dependent upon understanding the underlying processes and determining sufficiently accurate parameters. There are, however, examples in which insufficient understanding of the processes confounded predictions. The disease *Myxomatosis* was experimentally introduced onto the island of Skokholm, off the Welsh Coast, but did not persist and it thus was considered an unlikely control measure in the UK. However, *Myxomatosis* was subsequently introduced by farmers and it massively reduced the population of rabbits in the 1950s (the numbers have partly recovered since). The explanation was that, in the UK, *Myxomatosis* was spread by fleas, rather than by mosquitoes, and that, unusually, the rabbits on Skokholm do not have fleas (Lockley, 1954). As a second example, the parasite *Cyzenis* has been shown to play only a minor role in regulating winter moths *Operophtera brumata* in the UK, yet it acted as a very effective means of biological control in Canada where winter moth was previously a pest. The difference has been shown to depend upon the details of the predation of pupae in the soil (Hassell, 1980).

There are also examples in which species responded in an unexpected manner showing that the underlying processes were not fully understood. Brent geese were scarce in the UK and restricted to intertidal habitats where they fed particularly upon the plant *Zostera* spp. The *Zostera* had declined and there were a number of proposals to develop the areas of mudflat that they frequently used which was thought likely to greatly affect the geese. However, following a number of good breeding seasons in the Arctic, the numbers of geese increased and they then adopted the novel behaviour of feeding upon crops over the sea wall.

The confidence in the ability to predict will vary with the taxonomic group being considered. For example, the understanding of weed population dynamics seems good as there are only a narrow range of important weed species, their ecology is uncomplicated and it is reasonably straightforward to carry out experiments altering management or density (Freckleton and Watkinson 2002). It is possible to make reasonable predictions about the consequences of GM technology upon weed populations. However our understanding of invertebrate ecology is much poorer as there are a huge number of species, their ecologies are more complex and much less well understood and even measuring basic ecological information such as birth rate, mortality rate and density dependence is not straightforward.

Where there is the ecological knowledge available, as with weed populations, then models will be an important method for extrapolating to larger scales and to longer time periods. However in many cases, such as soil ecology, invertebrate ecology and breeding ecology of birds there is not yet the scientific background to use this approach with confidence.

The main environmental issue identified by this report is the consequences of GM HT crops. The herbicides under consideration are widely used, well researched and shown to have relatively small side effects. These broad spectrum herbicides have considerable potential for reducing weed populations with the potential for impacts on seed eating birds and species dependent upon the weeds (see Section 6.5). The results of the farm scale evaluation, due to be published in the autumn of 2003 and spring of 2004 will provide invaluable information on the consequences of these crops.

One response to uncertainty is the precautionary principle. For example, the European Commission communication on the precautionary principle states that "*Recourse to the precautionary principle presupposes that potentially dangerous effects deriving from a phenomenon, product or process have been identified, and that scientific evaluation does not allow the risk to be determined with sufficient certainty*." (Brussels, 02.02.2000 COM (2000) Communication from the Commission on the precautionary principle). However, our scientific review in this report of the environmental issues associated with proposed GM crops have not identified 'potentially dangerous effects'. The risks identified are comparable to those within existing practices for example from the escape of garden plants or changes in conventional agricultural practice. The exception is potential consequences of changes in management resulting from GM HT crops. After the farm scale evaluations have reported their results the implications of GM HT crops will be one of the most thoroughly researched ecological issue in the UK.

6.8.4 Is there general scientific agreement?

The range of approaches used for predicting the response to GM crops are the same as used in all branches of science. Scientists differ somewhat on the weight they would place on the different approaches and their confidence in the ability to predict, but there is widespread acceptance that these are the main standard methods. The approaches are reasonably well developed but the understanding of the underlying processes and parameter values vary considerably between subjects from good (e.g. weed ecology) to poor (e.g. soil ecology). There is a need for predicting the response to change to be a central component of biology and especially ecology.

6.8.5 Is the issue unique to GM?

Limitations in our ability to predict ecological changes within complex systems apply to a wide range of ecological issues and to many aspects of agriculture. For example, a wide range of agri-environment schemes exist with the purpose of improving biodiversity. Although often based on research their success is very mixed (Kleijn and Sutherland, in press). Although there were great concerns over the loss of hedgerows in the last few decades, in practice the change from spring sown cereals to autumn sown cereals and the greater stratification in farming with arable in the east and pasture in the west were probably of greater importance (Robinson and Sutherland 2001).

It should be pointed out that current widespread changes in agriculture with new crops, varieties, chemicals, equipment, and operations are also likely to affect biodiversity, yet typically receive negligible scrutiny.

The issue of GM crops becoming weeds is often considered alongside the comparable issue of the likelihood of the spread by alien species, especially from gardens. Predicting whether alien plants, of usually unknown ecology, will be invasive is probably considerably more difficult.

6.8.6 Are there gaps in our knowledge or scientific uncertainties and are these important?

In general, the potential level of harm will dictate the quality and quantity of information needed. For example, if protected species could possibly be affected, different information could be needed than if impacts could only be affecting common species. For example, changes to agroecosystems from the introduction of GM HT crops have a real possibility of affecting bird species on the biodiversity action plan priority list, and this was a driver behind the resources invested into the Farm-scale Evaluation programme.

A key issue is the pattern and extent of uptake of GM crops; i.e. "what farmers do". Models of the consequences of GM herbicide resistance showed that the pattern of uptake is critical (Watkinson *et al.* 2000): as only a small number of fields contain high densities of weeds the critical issue is whether these fields are particularly likely to be sprayed (for example to overcome the weed problem) or particularly unlikely to be sprayed (for example because the social, economic or ethical position that results in the farmer having high weed densities makes it unlikely that GM crops will be used).

There are clear gaps in our understanding of farmland ecology. However the research in GM HT crops is expected to be one of the most comprehensive analyses of ecological change. Furthermore the herbicides involved are widely known and well researched. The research shows that the side effects of these herbicides are generally less than selective herbicides (a number of which will be banned in 2003) but they are effective in killing non tolerant plants. The main direct impact is upon the weed populations and the ecology of these is well understood. The indirect impacts upon species feeding on these weeds are less well understood although the farm scale evaluation should reveal the implications for invertebrates. It is hard to predict the impacts that GM antifungal/antimicrobial crops might have on soil organisms and processes.

6.8.7 Likely future developments

With hindsight it is obvious that research being done now on herbicide resistant crops should have been done many years ago. It is similarly obvious on a global scale that the introduction of crops capable of growing in saline soils will lead to a wide range of questions and concerns (Sutherland and Watkinson 2001). There is a clear need to ensure that the science is done so that decisions may be made in an informed manner. This requires literature reviews, mathematical models and in some cases new observations and experiments.

Should the farm scale evaluations reveal significant environmental concerns then there are a range of policy options including allowing a mix of GM HT crops and measures to improve biodiversity. If this is on the agenda then it will obviously require forward planning and research if it is to be effective. There will also be the need for monitoring to see if such measures are effective.

6.8.8 Where there is important scientific uncertainty, what is the way forward?

Experiments are clearly essential to determine ecological impacts of some types of GM crops. However ecological results will often need to be placed within a theoretical framework to predict the wider consequences. For example, much of the concern relates to bird populations, yet the field experiments are not long enough nor on a large enough spatial scale to detect any direct impact on bird populations. This clearly requires models to consider the wider implications, especially for species such as birds whose ranges are enormously larger than the scales of experimental plots. Crop weeds have been declining over at least the last century (Robinson and Sutherland 2001) with obvious benefits to farmers, but costs to biodiversity. Detecting changes in weed populations over a short period will be difficult and this really needs to be placed within a theoretical framework to predict long-term responses.

For the issue identified as being of greatest current concern, the change in management resulting from the introduction of GM HT crops, a major source of information will be the farm-scale evaluations which compare split fields with half treated with GM HT crops and the other half managed conventionally with selective herbicides. The results from the crops planted in the spring should be available in the autumn of 2003 while the results for the autumn sown crops should be published in the spring of 2004. These should greatly improve our understanding of the subject.