BIOTECHNOLOGY IN THE ENVIRONMENT: POTENTIAL EFFECTS ON BIODIVERSITY

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Summary

The use of recombinant DNA (rDNA) technology to introduce novel traits into living organisms represents a quantum leap in our ability to manipulate the agricultural environment. As the technology has developed over the last thirty years, our understanding of the risks involved in creating transgenic crops has evolved, yet is still far from complete.

It is widely, although not universally, recognised that transgenic crops pose unique risks to the environment, such as toxicity and gene transfer, over and above those posed by conventionally bred plants. Furthermore, our ability to design crops with specific combinations of traits to suit human needs may impact the environment on a larger scale, by catalysing land-use changes which could potentially have adverse impacts on

biodiversity.

Biotechnology is a valuable tool and could eventually contribute towards more sustainable management of physical and biological resources. However, the technology could also be used for short-term gain, without regard for the environment. It is crucial for ecologists, conservationists and population geneticists to be closely involved with the development of transgenic crops from conception to release and monitoring, to ensure that risks to biodiversity are minimised, and benefits realised.

1. Introduction

1.1. Agriculture and biodiversity

Agriculture can be described as creating modified ecosystems, managed to provide a concentrated source of food, fibre or energy. Besides this function, cropped areas also provide habitats for many native and naturalised species. Some agricultural systems are over 3000 years old, older than some ecosystems (such as heathlands) regarded as ‘natural’, so there has been time for species to develop dependence on agricultural systems for all of or part of their life cycle. Most agricultural landscapes also contain remnants of original ecosystems in the form of hedges and ditches, woodlands, wetlands and grasslands In regions where agriculture is the dominant land use, farmland is increasingly important as a refuge for species whose natural habitats have been eliminated or seriously degraded by other human activities [*see also – Agricultural Biotechnology*].

Non-crop biodiversity provides crucial ‘ecosystem services’ which include maintenance of soil fertility, regulation of pests and pollination of the crop. However, it is generally true that the greater the biomass of non-crop organisms, the lesser are resources available for the crop itself. This has led humans to simplify agricultural ecosystems by reducing or eliminating weeds and crop pests, together with much non-target biodiversity. The increasing success of these strategies has brought greater crop yields, but has come at the expense of long-term sustainability, as farming relies more and more on external inputs to support the demands of nutrient-hungry crop varieties and to fend off ever-tougher pests and weeds.

Since agriculture covers large parts of the earth, characteristics of crops and their management regimes are important for the conservation of a significant proportion of world biodiversity *[see also - Biodiversity: Structure and Function]*. The challenge for the future is to develop ways of producing a stable and adequate food supply whilst safeguarding natural biodiversity. This is likely to be achieved through a combination of careful management and the breeding of more appropriate crop varieties.

1.2. Background to crop breeding

For several millennia, humans have striven to improve the quality and quantity of their agricultural food resource through the development of more suitable crop varieties **[***see also - Traditional plant breeding for yield improvement and pest resistance***]**. The use of genetic engineering to improve crop plant varieties can be seen as a ‘natural’ extension of plant breeding, in the sense that the goals are still the same. In the technical and ethical senses though, genetic engineering – also referred to as 'modern biotechnology' to distinguish it from traditional applications of biotechnology such as the use of yeast in bread-making which do not entail the manipulation of genomes – is a radically new technology with a whole range of potential biosafety implications.

Domesticated crop species today bear little or no resemblance to their wild progenitors. Selective breeding by humans over hundreds or thousands of years has altered wheat and maize almost beyond recognition, to the stage where they can no longer form viable populations in the wild. From wild genetic material, humans have both consciously and unconsciously selected for traits which make plants into better food sources: faster growth; greater productivity; higher nutritional value; easier management and harvestability.

Despite the undoubted success of crop breeding in enabling humans to establish more or less reliable food supplies for growing sedentary populations, there are still a number of constraints on agricultural production. Many (although not all) of these constraints result from the fact that the crop varieties currently available to us are still far from ideal in terms of their efficiency and environmental impact. The ideal crop variety would probably be perennial, tolerant to weed populations, pest and disease resistant, nitrogen fixing, rapidly maturing, easily harvested and a highly nutritious food source. It would have highly efficient photosynthesis and nutrient use, perhaps produce several crops per season, provide good quality wildlife habitat and require little or no management.

Natural genetic variation present in crop/wild relative gene pools can allow crop varieties to be adapted to suit local conditions, and mutagenesis can occasionally achieve substantial (although essentially random) improvements. It is increasingly clear that the kinds of traits breeders would really like to see in crops may only be attained by exploiting genetic material that is inaccessible by conventional breeding methods. Furthermore, plant breeding is an increasingly commercial enterprise. The introduction of novel and useful agronomic or quality traits can add significant value to a crop variety and the biggest companies have access to markets all around the globe. These reasons, coupled with the fact that our understanding of genetics has increased exponentially in the latter half of the 20th century, explain the growing interest in genetic engineering for the improvement of crop varieties.

However, crop breeding has, over time, resulted in a gradual but accelerating erosion of genetic diversity within crop gene pools [see also - *Magnitude, Distribution and Characteristics of Change in Biodiversity; - Biotechnology and agro-biodiversity*] as local landraces are lost to commercially produced brands. Homogenisation of crop gene pools means fewer and fewer options available for breeding of natural resistance into commercial crop varieties. Commercial varieties are often more susceptible to pests and diseases and so require higher pesticide inputs; this is particularly true of varieties planted as monocultures across large areas of countryside. Specific traits now being incorporated into crop varieties have enabled changes to more environmentally damaging agricultural practices, for example the widespread adoption of autumn sowing in temperate regions. New varieties are constantly being developed to extend the range of agronomic options for both forage crops (especially maize and legumes), and food and industrial crops such as potatoes, oil-seeds and cereals. In many areas, this is leading to more specialisation and a decline in traditional mixed farms, with their biodiversity-rich mosaics of forage areas, patches of native vegetation and arable fields.

1.3. Traditional breeding versus genetic engineering

There has always been considerable disagreement within the scientific community over whether genetic engineering is merely an extension of traditional plant breeding methods or whether it is a fundamentally new technology and therefore more unpredictable and risky. This has led to a divergence of views on how to assess the various potential risks of transgenic crops [see also - *Transgenic plants*]. Those who believe the former argument advocate a *product-based* approach to risk assessment, in which the technique used to create the crop variety is not seen to be inherently risky, and environmental risk assessment focuses on the phenotypic characteristics of the plant. Under a product-based approach, conventionally bred and transgenic plants with similar traits would be assessed in exactly the same way. Those who believe the latter, advocate a *process-based* approach, where transgenic crops are assessed separately and in far greater detail due to their special risks.

Regal argues strongly for a process-based approach to risk assessment on the grounds that transgenic organisms differ from conventionally bred varieties in at least three fundamental ways:

- Phylogenetic leapfrogging. Traditional breeding has largely been limited to exchange of genetic traits between populations where the genetic differences are typically minor to begin with. Genetic engineering can move fully functional genetic traits between different phyla. While this kind of leapfrogging may not in itself be inherently dangerous, it offers unique opportunities to create ecologically competent organisms with novel combinations of adaptive traits.
- Avoidance of genetic trade-offs. Selective breeding almost always results in trade-offs, where alleles conferring traits conducive to agricultural production have gradually replaced ‘wild-type’ alleles in the crop genome, to the extent that most ‘domesticated’ crops are now no longer able to form self-sustaining populations in natural ecosystems. Genetic engineering enables adaptive traits to be added to the genome of an ecologically competent host without the potential loss of wild-type genes, and is therefore more likely to enhance the fitness of the transgenic plant in the wild than is selective breeding.
- Access to non-Mendelian portions of the genome. Many phenotypic features are highly conserved, due to functional genetic monomorphism, and cannot be changed by selective breeding. Traditional breeding has thus been largely restricted to modification of those phenotypic traits that vary in Mendelian fashion. Although mutagenic breeding has enabled changes in these inaccessible parts of the genome, these have been largely haphazard. In contrast, genetic engineering offers the prospect of systematically reprogramming an organism’s basic genetic command systems, which could create highly competitive novel organisms.

These arguments do not define all transgenic organisms as hazardous, but they do demonstrate the ability of modern biotechnology to create more radical transformations than has been possible via conventional means. They thus justify the stance currently taken by the majority of regulatory systems that genetically engineered organisms generally merit more stringent risk assessment than their selectively bred counterparts.

Furthermore, some transgenes can function in a very different way from naturally occurring genetic mechanisms, and this could imply additional risks to the environment. For example, transgenic viral resistance is typically produced by inserting a gene encoding for a viral coat protein into the plant genome, whereas wild-type plant genomes never contain coat protein genes. This could increase the risks of recombination between the transgene and a second invading virus to create a novel virus with new properties.

Nonetheless, as experience and understanding of transgenic organisms has accumulated over the years, the emphasis of risk assessments has gradually moved from process-based towards a more product-based approach. During the early stages of genetic engineering experiments, questions were asked about the safety of the transformation process itself. In time, these fears subsided and attention focussed on safety of transgenic organisms in the environment. With widespread commercial release now a reality in several countries, attention is beginning to turn to the environmental consequences of the new agricultural systems enabled by this revolutionary technology. The impacts of crop biotechnology on the environment must be understood at all these levels, and this knowledge used to manage and regulate the technology wisely, if adverse consequences for biodiversity are to be avoided and benefits realised.

2. Defining ecological risk

The composition of biodiversity in both farmed areas and natural ecosystems is constantly changing, because of physical conditions such as climate change and pollution, intrinsic ecological factors including cyclical changes in predator/prey relationships and changes in the population genetics of component species, and the direct impacts of management by humans [see also - *Biodiversity and ecosystem function*]. Agricultural intensification is probably the most dominant trend affecting the ecology of farmed landscapes, as illustrated by recent large declines in European bird populations dependent on cropped and pastoral landscapes. In intensive farming areas populations of many farmland specialists have fallen by over 60 percent, with some species becoming extinct over large parts of their former range. Drainage and unsustainable harvesting are among the main anthropogenic factors causing natural ecosystems to change – usually, but not always, resulting in lower biodiversity.

Defining ecological risks arising from transgenic crop varieties must be considered against this background of instability. It is therefore important for regulatory authorities to understand the inherent characteristics of vulnerable ecosystems within the release territory, and to understand the ecological relationships between those ecosystems and farming activities. Characterising the nature of change in agricultural and natural ecosystems likely to be affected by a transgenic crop should be an important first step in ecological risk assessment. A useful second step may be to define target levels for biodiversity, and to assess the impact of introducing a new crop variety or management regime against these targets. If, for example, trends in population dynamics of species within such ecosystems are identified as upward, downward or cyclical, then the potential effects of introducing a transgenic crop should be considered in that context. Assuming that ecosystems in contact with crops are stable may be incorrect and unhelpful.

In risk assessments of transgenic crops, it is not enough simply to identify possible effects, such as the creation of invasive plant varieties or toxicity to wildlife. This information identifies a possible *hazard*, but does not quantify *exposure* to that hazard, i.e. the rate of hybridisation between crops and wild relatives or the frequency of contact between transgenic toxins and susceptible organisms. 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, 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 and lacewings. 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. When this comparison was made in a series of experiments by Sears and coworkers in 2001, the Bt toxin in maize pollen was shown to have a negligible effect on Monarch butterfly populations in and around maize fields. In the case of assessing changes in field management enabled by herbicide tolerant (HT) transgenic crops, a valid comparison might be with the effects of herbicide regimes used on conventional crops. Such 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. A three year ecological experiment comparing ecological impacts of the management of HT crops with conventional herbicides in the UK (the “Farmscale Evaluations of GM Herbicide-Tolerant Crops”) found that the management of transgenic HT oilseed rape (canola) and beet had adverse impacts on farmland biodiversity compared to conventional herbicide treatments, whereas management of transgenic HT maize had significant benefits for farmland wildlife in the UK.

In the UK, a process known as the ‘Biodiversity Action Plan’ has been used to set targets for populations of declining farmland birds within a regional context. Studies of the ecological needs (the ‘autecology’) of some of these species have revealed what resources are critical to the breeding success of these birds. Research is now under way to identify how growing transgenic herbicide tolerant crops may affect the availability to these birds of critical resources such as weed seeds and insects. The process being used here is therefore:

- Defining ecological targets for selected species within the relevant area
- Identifying critical resources needed by these species, provided by farmland

- Carrying out research to assess the effects of growing transgenic crops on these resources
- Assessing the (indirect) risks to these species from growing the transgenic crops in relation to the crop systems they are likely to replace, and identifying possible risk management procedures to minimise risks.

Identifying ecological risk from transgenic crops therefore requires good scientific information. In some circumstances there may be a need to construct models in order to predict what effects there may be on specific ecosystems from a particular transgenic trait such as herbicide tolerance. Watkinson and his research team have developed recently a simple model for a bird/weed/crop (skylark/*Chenopodium*/sugar beet) food chain which provides a conceptual framework for assessing potential effects on birds of growing transgenic HT crops. However, in order to be useful for predicting risk, such models must be populated with realistic parameters, gathered by both field and laboratory studies.

2.1. Framework for ecological risk assessment

2.1.1. Ecological risks from transgenic crops

With the advent of biotechnology, more options for novel traits within 'traditional' plant varieties are becoming available, changing either the characteristics of the plants themselves, or enabling changes in crop management regimes [see also - *Plant breeding and molecular farming*]. These crops are often agronomically more attractive to growers and are quickly replacing conventional crops, especially in North and South America. Since some of these crops (such as insect resistant maize and cotton) contain substances potentially toxic to wildlife, and others (such as herbicide tolerant crops) may trigger changes in agrochemical regimes, it is important that regulatory authorities assess ecological risks stemming from these crops.

Almost all systems regulating the release of transgenic crops now recognise that ecological risks may arise from agricultural biotechnology. Some risk assessment protocols incorporate a framework for assessing such risks, and applicants seeking consent to release transgenic crops are usually required to assess the *direct* risks (i.e. risks stemming from direct interactions between the crop and its environment) arising from possible toxicity and other crop characteristics. Direct risks include risks posed by potential gene flow either to conventional crops or to wild relatives of the crop. In addition, a few regulatory regimes also assess potential risks to biodiversity from *indirect* effects of changes in crop management or use or geographical range *enabled* by the transgene.

Factors leading to ecological risks from transgenic crops, and the classification of such risks, are illustrated in Figure 1.

2.1.2. Defining ecological harm

Ultimately the degree of ecological harm deemed to be acceptable is often a political decision rather than a purely scientific exercise. Science can and should inform such a decision, but levels of ecological harm which trigger refusals of consent to release transgenic crops cannot be defined entirely objectively. An exception would be if the level of ecological harm threatened the viability of an existing population, especially of a ‘keystone’ species, whose extinction could threaten an entire ecosystem.

Countries that have adopted the Convention on Biological Diversity are under an obligation to conserve their biodiversity, and this often includes species that have become dependent on farmland. It is widely agreed, and codified in international treaties and domestic laws, that species extinctions are unacceptable, so it is possible to define the most unacceptable level of ecological harm *as that which threatens the viability of a species or a distinct population of that species*. By that definition, conventional intensive agriculture in some parts of the world is already causing unacceptable ecological harm. The overall test for ecological harm from transgenic plant varieties in future may be whether they add to or subtract from the harm to the world’s ecosystems caused by conventional agriculture or other human activity, but the degree of harm that is acceptable is always going to be a matter for informed judgement.

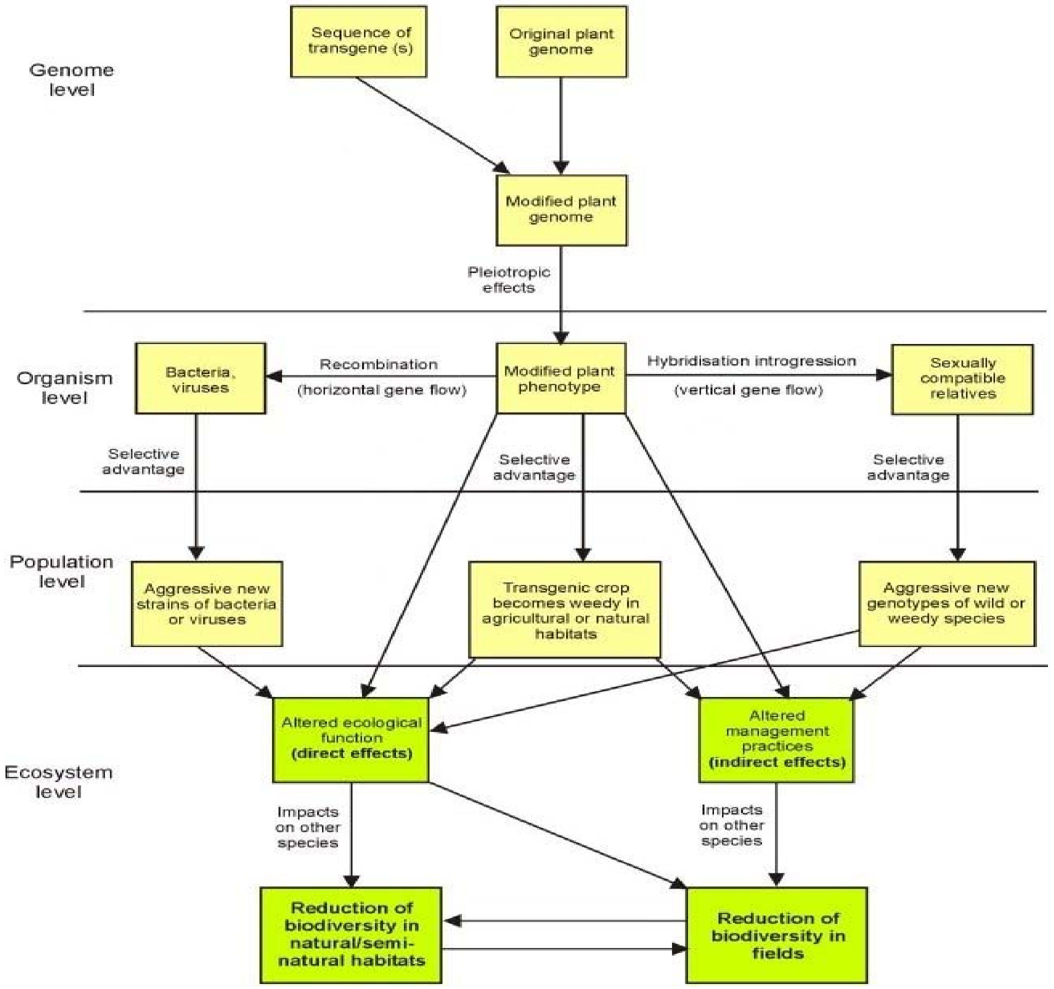

Figure 1: The potential risks of transgenic plants

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Biographical Sketches

Dr Brian Johnson was until December 2005 senior advisor on biotechnology to the British statutory nature conservation agencies and head of the Biotechnology Advisory Unit at English Nature (now Natural England), the UK government's advisors on nature conservation in England. He has been in the centre of the debate on potential effects of GMOs on biodiversity and other aspects of the environment in Europe. After pursuing academic research on population genetics and ecology, he has spent the last 18 years in nature conservation. He has written numerous articles about conservation and the impacts of biotechnology and sits on several advisory committees concerned with biotechnology and the environment. He has also written a number of articles on bioethics.

Anna Hope is assistant specialist advisor on biotechnology to the British statutory nature conservation agencies. After completing a degree in biological sciences at Oxford University, UK, Anna spent time working on environmental projects in Latin America and Spain before deciding to specialise on issues surrounding biotechnology and the environment. Prior to her current position at Natural England, she worked in the School of Biological Sciences at Bristol University.