Environmental Impact of Genetically Modified Organisms (GMOs)

Advanced article

Article Contents

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Based in part on the previous version of this Encyclopedia of Life Sciences (ELS) article, Impact of Genetically Modified Organisms (GMOs) by Maurizio G Paoletti.

The intensification of agriculture has provided cheaper more plentiful food, but has also caused declines in farmland wildlife. The introduction of genetically modified (GM) crops may exacerbate this, or offer new ways of mitigating anthropogenic impacts. The potential consequences of the introduction of GM crops have been studied for over a decade, since commercialization. Although the specific issues depend on the crop and transgenes involved, one common theme that emerges is that the biggest effects will arise from the way in which the GM crop will be managed. Herbicide-tolerant GM crops may allow better weed control, and this is a risk to biodiversity that should be mitigated. However, even herbicide-tolerant crops have some environmental benefits through reduced production and application of herbicides. Insect and disease-resistant crops will have fewer impacts on nontarget organisms than conventional crops and their management, and so may offer direct environmental benefits.

Introduction

Despite the application of 2.5 million tonnes of pesticides worldwide, more than 40% of all potential food production is lost to insect, weed and plant pathogen pests before harvest. After harvest, an additional 20% of food is lost to another group of pests. The use of pesticides for pest control results in an estimated 26 million human poisonings annually worldwide. In the United States, the environmental and public health costs for the recommended use of pesticides total approximately $9 billion per year. Thus, there is a need for alternative pest control methods that do not involve synthetic chemicals to reduce these costs and associated health and safety risks. Genetic modification of crops may provide some novel alternatives that fulfill these criteria. Disease and insect pest resistance to various pests has been slowly bred into crops for the past 12 000 years; current techniques in biotechnology now offer opportunities to improve the control of disease and insect pests of crops more rapidly and by using novel mechanisms. **See also**: Agricultural Production; Genetically Modified Plants; History of Scientific Agriculture: Crop Plants; Plant Breeding and Crop Improvement; Plant Transformation; Transgenic Plants

The introduction of any new technology also involves new hazards and risks. In Europe, much of the recreational countryside lies alongside agricultural land, and a proportion of wildlife is dependent on the management of farmland. Past changes in agricultural practice – such as land drainage, hedgerow removal and the switch from spring sown to autumn sown crops – have contributed to the decline in arable plants (25% of which are now Biodiversity Action Plan species), the insects which rely on them and ultimately to farmland bird populations (Benton *et al.*, 2002). Consequently, the debate about the environmental impact of GM crops has been contentious in Europe. A second important environmental issue of our age is the threat of climate change. Intensive farming makes a significant contribution to global warming through the production and application of herbicides, pesticides and fertilizers (Desjardins *et al.*, 2007). It is into this context that the potential environmental impact of GM crops should be considered. Will they change agricultural practice in a way that will further exacerbate declines in wildlife across Europe? Alternatively, will they permit a reduction in the production of gases that contribute to the global warming potential (GWP) of agricultural practices? The evidence to assess the impacts of GMOs is gathering in the scientific literature, although the frameworks within which to make holistic assessments are not yet routinely used in the risk assessment of these organisms. **See also**: Agricultural Systems: Ecology; Climate Change and Biogeochemical Impacts; Plant Biodiversity

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The commercial cultivation of GM crops started in the United States over 10 years ago in 1996, rising to 25 countries planting approximately 125 million hectares in 2008 (James, 2008). The principal traits are insect resistance (using largely toxins derived from *Bacillus thuringiensis*) and herbicide-tolerant crops, with a very few examples of crops resistant to diseases. The United States, Argentina, Brazil, Canada, India and China plant the greatest areas, with much less grown across many African countries (with the exception of South Africa) or Europe. Before being placed on the market, any GM crop needs to undergo an environmental risk assessment (ERA). The details of this process differ across the world, but the essential elements considered are the same (Hails and Kindelerer, 2003). In Europe, these are defined as unintended effects on plant fitness, the consequences of gene transfer, resistance development in target organisms, adverse effects on nontarget organisms, effects on human and animal health exposed to the GM plant, effects due to altered cultivation and management of the crop, potential impacts on biogeochemical cycles and the interaction with the abiotic environment. The debate about the environmental safety of GMOs has probably been most vigorous in Europe, and this has led to over a decade of worldwide experimental research on all of these topics. This is not a comprehensive review, but a précis of the most important elements of that research, with a focus on impacts on nontarget organisms, both directly and indirectly, through altered cultivation and management practices.

Herbicide-tolerant Crops

Genetically modified herbicide-tolerant (GMHT) crops are modified to be resistant to one of the two broad-spectrum herbicides, glyphosate or glufosinate ammonium. GMHT crops were designed to provide the farmer with an easier and more effective weed control programme. The potential consequences of this could be that weeds will be so effectively eradicated from arable fields that this will exacerbate declines in farmland wildlife. To answer this question a series of trials were funded by the UK government from 1999 to 2003 (Firbank *et al*., 2003a, 2003b). The design of these trials was very simple: farmers' fields were divided into two, and in one half a conventional crop was grown and managed as usual, whereas in the other half the GMHT crop was grown and managed following industry guidelines. Biodiversity was monitored in both halves of the field. These trials involved four crops (spring oilseed rape, sugar beet, fodder beet and forage maize) and were replicated across the UK over three years. Two very clear messages emerged from these experiments, the first concerned management and the second biodiversity. The weeds in GMHT crops were managed with one or two sprays, as recommended, whereas the conventional crops were managed between 1.6 and 4 sprays on average, depending on the crop (see **Figure 1**; Champion *et al*., 2003).

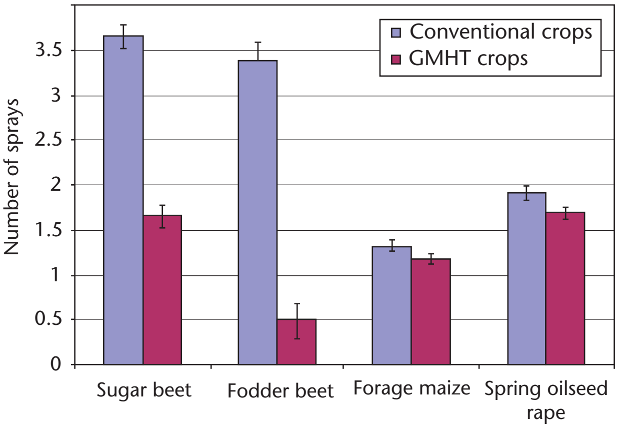

Figure 1 The mean number of applications of herbicides (±SE) applied during the Farm Scale Evaluations. Data taken from Table 2 of Champion *et al.* (2003). Figures include pre-drilling applications and, for spring oilseed rape, desiccants.

However, the average number of sprays does not necessarily equate to the impact on biodiversity. For both sugar beet and oilseed rape, the GMHT system led to more effective weed control and ultimately this would be likely to have an adverse effect at higher trophic levels (e.g. farmland birds). These small but significant differences were reversed for maize (see **Figure 2**; Firbank *et al*., 2003a, 2003b; Heard *et al*., 2003a, 2003b). As a result, the UK advisory committee recommended that these GMHT crops should not be grown following these management guidelines in the UK (ACRE, 2004).

The farm scale evaluations (FSEs) demonstrated that GMHT crops may contribute to declines in biodiversity *if managed according to specific guidelines*. Further research then turned the question around, and investigated whether the flexibility offered by the GMHT-cropping system could be used to enhance biodiversity without impacting on crop yield. GMHT crops are designed so that herbicide treatments may be later than usual (postemergence), but spray could also be applied earlier than usual, allowing late germinating weeds to survive and mature to set seed. Alternatively, early sprays could be confined to the rows within which the crop is growing, with weeds being allowed to flourish in-between rows until a later date. Exploiting this potential for temporal and/or spatial flexibility in treatment, it has been illustrated both empirically (May *et al*., 2005) and theoretically (Freckleton *et al*., 2004) that biodiversity may be maintained in GMHT sugar beet without compromising yields. However, this may be at the expense of some inconvenience to the farmer, either through the enforcement of nonstandard spraying patterns or through the presence of significant quantities of dead weed material in the field at harvest.

The simplest mitigation measures would involve leaving field margins unsprayed, or even actively managing other parts of the farm for targeted biodiversity benefits (Hails, 2002). Using FSE data it was estimated that between 2% and 4% of the crop area would need to remain untreated

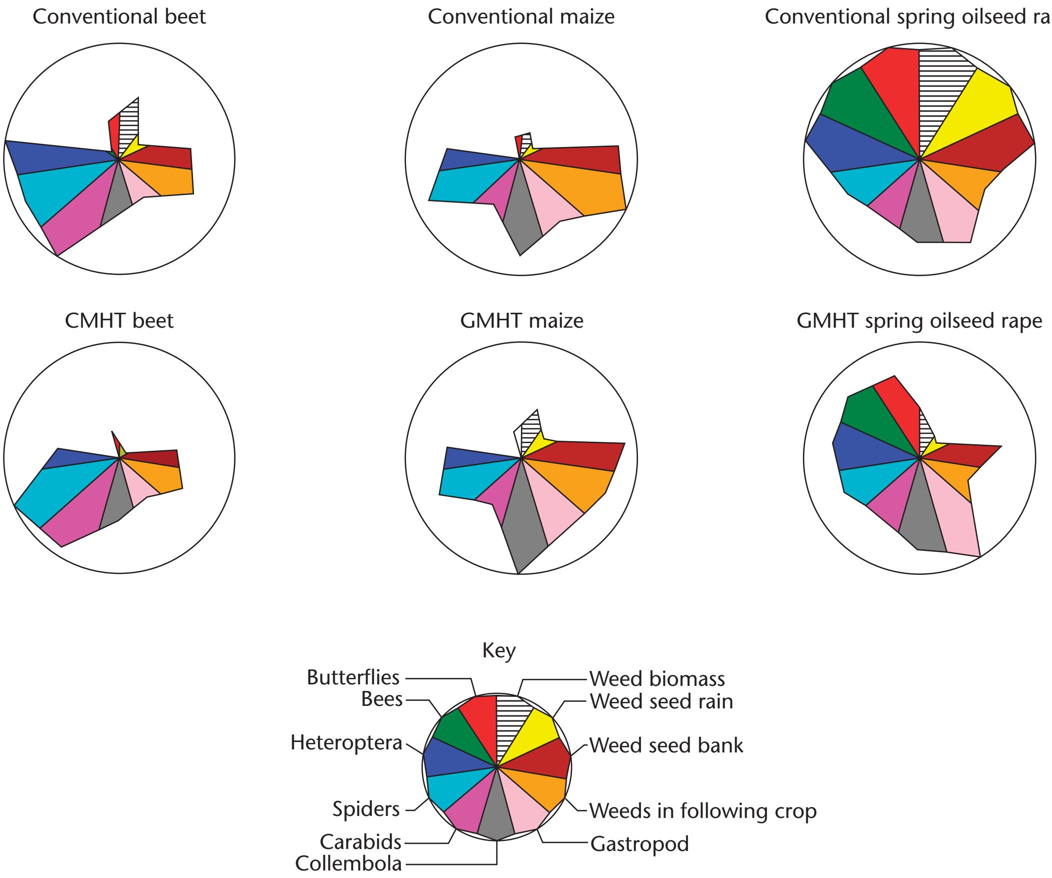

Figure 2 Star plots comparing biodiversity indicators across conventional and GMHT crops. For each indicator, the length of the star corresponds to the value relative to the maximum value found for that indicator in any of the six combinations of crop and treatment (e.g. the maximum values for bees and butterflies were found in conventional spring oilseed rape). The key shows which section of the star diagram represents which indicator. Reproduced from Firbank *et al.* (2003b). www.defra.gov.uk/environment/gm/fse/results/fse-commentary.pdf. With permission of the Department of the Environment, Food and Rural Affairs.

(either unsprayed or even unsown) to mitigate against the more effective weed control in the GMHT-managed crop (Pidgeon *et al*., 2007). This translates approximately into a tilled margin width increase from 0.5 to 1.5 m, and would be cheap and simple to implement and enforce.

The debate has widened over the last decade to consider other environmental consequences of agricultural practices. Life cycle assessment (LCA) has emerged as a useful tool with which to compare the environment and human health impacts of products or processes (SETAC, 1991). When applied to the growing of GMHT sugar beet, the conclusion was that the growing of GMHT sugar beet would result in lower impacts to the environment and human health than the three conventional systems used for comparison (Bennett *et al*., 2004). This was largely due to lower emissions from herbicide manufacture, transport and the number of field operations. In particular, those elements that contribute to global warming, ozone depletion and nitrification of water (among others) were much lower for GMHT crops. **See also**: Energy Use in Agriculture

In summary, the potential for more efficient weed control using GMHT-cropping systems represents an environmental hazard that could exacerbate the biodiversity declines observed over the last four decades. This hazard may be mitigated, and other wider environmental benefits may make such mitigation measures worthwhile.

Insect-resistant Crops

Cry proteins from the bacterium *Bacillus thuringiensis* are the most common insecticidal proteins that have been engineered into plants, including the crops maize, cotton, potato, tomato, rice, eggplant and oilseed rape, with only maize and cotton being widely commercialized.

There are concerns that insect-resistant GM crops expressing Cry proteins could harm insects other than the target pests. Since GM insect-resistant (GMIR) crops were first commercialized, over 100 scientific papers have been published investigating nontarget impacts in the field. When a significant body of work has been published on one topic, meta-analysis is a useful technique to quantitatively review the evidence. A meta-analysis of 42 independent field experiments indicated that nontarget invertebrates were generally less abundant in Bt maize or cotton than in control fields of the isogenic crop (Marvier *et al*., 2007; Wolfenbarger *et al*., 2008). Unsurprisingly, nontarget arthropods closely related to the targets do appear to be reduced in abundance in some cases: for example, nontarget Lepidoptera are less abundant in Bt cotton which targets Lepidopteran pests. However, when the GMIR crop is compared to the conventional crop treated with insecticides, nontarget arthropods are more abundant, and these differences are greater in magnitude (Marvier *et al*., 2007).

Invertebrate predators may be exposed to Bt toxins when they feed on prey that have previously fed on a Bt crop. There has been some debate over the extent to which this may have an impact on predators. For example, there is clear evidence for the uptake of biologically active Cry1 protein by the green lacewing, *Chrysoperia carnea*, via its herbivore prey (Obrist *et al*., 2006). However, direct effects are thought unlikely due to their specific toxicity (e.g. Cry1Ab to Lepidoptera). Neither literature reviews (Romeis *et al*., 2006) nor meta-analyses of field trials (Marvier *et al*., 2007; Wolfenbarger *et al*., 2008) have concluded that there are direct adverse effects on invertebrate predators in the field. Parasitoids respond more sensitively to the presence of Cry proteins in the diet of their hosts, with significant reductions in survival, development time and cocoon weights (Lovei and Arpaia, 2005). The specificity of the Cry proteins again makes direct effects unlikely, and these impacts are more likely to be associated with the poor quality of their hosts (Vojtech *et al*., 2005).

In contrast, one study compared six pairs of transgenic maize lines with their isogenic counterparts, and in five of six cases found that the Bt maize was more susceptible to aphids. Slightly, but significantly elevated amino acid levels in the phloem may be responsible for the enhanced aphid performance. As a consequence, one parasitoid species (*Cotesia marginiventris*) which feeds on aphid honeydew lived longer and parasitized more pest caterpillars in the presence of Bt maize than the isogenic lines (Faria *et al*., 2007). This provides an example of an unintended beneficial effect of Bt maize.

The development of insect resistance to transgenic crop varieties is one of the most likely adverse consequences of GM crop cultivation, and this could impact on the use of Bt in insect pest management programmes. Many insect species have been shown to contain genetic variation to Bt toxins, and so possess the potential to evolve resistance. To manage this risk, the refuge strategy has been employed. The theory behind this strategy is that a percentage of the cropped area should contain a non-Bt variety, allowing susceptible individuals to survive. Any rare resistant individuals surviving from the Bt crop will then mate with the susceptible individuals from the refuge and produce susceptible offspring (Gould, 1998). Long-term global-monitoring data has discovered that the frequency of resistance alleles has increased significantly for one pest (*Helicoverpa zea*), but not for five other major pests (Tabashnik *et al*., 2008). *Helicoverpa zea* is a pest of cotton, and its control has always been augmented by other measures, hence this has not resulted in widespread control failure. Evidence also suggests that the refuge strategy has delayed the development of resistance – nevertheless this is a cause for concern. Cotton containing two cry toxins targeted against *H. zea* is now increasing its market share in the United States, and it is predicted that this will reduce the resistance problem (Tabashnik *et al*., 2008).

Disease Resistance in Crops

Relatively few crops have been commercialized to be resistant to disease, and most of these have been engineered to be resistant to viral diseases. These include squash, papaya, plum, grape and sugar beet. The advent of GM techniques allowed coat protein genes derived from the pathogen itself to be inserted into the plant genome and so confer resistance – a phenomenon known as pathogen-derived resistance (PDR). Arthropod vectors of viruses are routinely controlled by pesticides, usually in combination with cultural methods – so the immediate benefits of GM varieties are a reduction in the chemicals applied, with all the associated benefits outlined in the earlier section, and also increases in yield, as GM varieties have proved more effective and enduring. **See also**: Epidemiology of Plant Virus Diseases; Luteoviruses; Viruses and Plant Disease

The transfer of the genes conferring resistance to wild relatives could conceivably lead to natural enemy release, with the wild relative becoming more abundant, even invasive, in seminatural habitats. One example of this is the GM virus-resistant squash (*Curcubita pepo* spp. *ovifera* var. *ovifera*) which will hybridize with wild squash (*Curcubita pepo*). One argument for the deregulation of this GM crop was that the target viruses were not found in populations of the wild relative *Cucurbita texana* (Kling, 1996). Studies of viruses in wild populations of *Brassica* species (Raybould *et al*., 1999, 2003; Thurston *et al*., 2001; Pallett *et al*., 2002) suggest that it would be unwise to assume that the absence, or rare occurrence, of a particular virus in a particular species was an indication that transgenes conferring resistance would have no effect (Hails and Gray, 2004). On the contrary, viruses rare or absent from particular plant populations tended to severely reduce growth or kill plants of those species under experimental conditions. Conversely, common viruses often have no effect on growth. For example, the most widespread virus in wild populations of wild cabbage *Brassica oleracea*, *cauliflower mosaic virus* (CaMV) has no measurable effect on that species, but killed or severely restricted the growth of young plants of wild mustard *Brassica nigra* and wild turnip *Brassica rapa* in whose wild populations it is rare or absent. Similarly, *turnip mosaic virus* (TuMV) is almost never found in *B. nigra* or *B. rapa* populations and these species are highly sensitive to challenge by manual inoculation, wheras *B. oleracea*, in which TuMV is more common in the wild, merely shows reduced seed output (Thurston *et al*., 2001; Raybould *et al*., 2003). Viruses may be moved between plant populations via their vectors, so the arrival of a rare pathogenic virus could have a very different impact depending on the presence or absence of pathogen resistance transgenes.

Predicting the potential and magnitude of enemy release when novel disease resistance genes are introduced into populations remains one of the key issues in the risk assessment of disease-resistant crops. Quantitative frameworks have been developed to assess these risks, and populated with data from GM and conventionally bred virus-resistant clover (*Trifolium repens* resistant to *Clover yellow vein potyvirus*). This illustrates that there could be enhanced fitness, and expansion of the host plant into some marginal environments (Godfree *et al*., 2007). This remains a risk that must be evaluated on a case-by-case basis.

Some plant pathologists have also suggested that development of virus-resistant crops could allow viruses to infect new hosts through heteroencapsidation. The concept is that coat protein genes expressed by the transgenic plant form the coat of an infecting virus, and so allow, for example, an otherwise vector-nontransmissible virus to become transmissible via vectors and so change its host range. This phenomenon has been reported to occur at low frequency in at least one example (Fuchs *et al*., 1999). However, these changes are for a single generation, as the viral genome is not affected so subsequent virus progeny is encapsulated in their usual coat proteins. Therefore, this has been judged to be of limited environmental significance (Fuchs and Gonsalves, 2007). Similarly, the posited risk of recombination between the coat protein genes and invading viruses to produce novel, pathogenic genotypes is now judged not to represent any significant novel risks (Fuchs and Gonsalves, 2007; Turturo *et al*., 2008).

Future Opportunities for Environmental Protection

There are a number of novel crops at various stages in the development pipeline that could significantly ameliorate the impact of man on the environment. The use of nitrogen fertilizer has increased dramatically over the last 50 years, and its production has a GWP 300 times greater than carbon dioxide. A large proportion of applied nitrogen is not taken up by crops, but is leached out by rain, contaminates ground water and causes eutrophication. Oilseed rape has been genetically modified to increase its nitrogen use efficiency, and a partial life cycle assessment of this GM crop calculated a range of environmental benefits relative to conventional oilseed rape, particularly in reductions of greenhouse gases and diffuse water pollution (Strange *et al*., 2008).

Another example includes the development of potatoes resistant to cyst nematodes. Currently, fumigant and carbamate nematicides are used to control these pests, although several of these synthetic chemicals are being withdrawn because of concerns for impacts on human health and the environment. Root exudates from a GM potato express a synthetic peptide which disrupts the nematodes host-finding behaviour, and this could prove to be an effective alternative method of control (Liu *et al*., 2005).

Finally, there are potential roles for GM plants moving beyond agriculture. There are currently a limited number of options to deal with land contaminated by pollutants. Solutions include removal of polluted soil to landfill, incineration or covering over (e.g. with concrete), none of which is sustainable in the longer term. Transgenic plants are being developed to work in consortia with indigenous bacteria to operate as environmental cleanup biosystems (Macek *et al*., 2008; Rylott and Bruce, 2009), for example, to enhance mercury phytoremediation (Ruiz and Daniell, 2009). The role of a GM plant in remediation may be 2-fold: to accumulate or metabolize the contaminant, but also to selectively support the metabolism and survival of degrading bacteria in the rhizosphere (**Figure 3**).

Such applications of genetic modification will also require a careful assessment of the risks. Edible plant species should be avoided, and containment measures may be required to avoid gene flow to wild relatives.

Discussion – The Future of Risk Assessment

Considerable data on the environmental impact of GM crops, and particularly the consequences for biodiversity, have been collected through experimental studies and from observations on commercial fields for over a decade and a half. There is a better understanding of the potential impacts on biodiversity, the mechanisms by which potential risks may be mitigated, and also the potential benefits that GM cropping systems may offer. Over the last few years, an urgency has also developed over the requirement to reduce the GWP of many of man's activities, with agriculture as one of the significant contributors to greenhouse gases. It is therefore imperative that the risks and benefits of GM crops are compared with those of conventional agriculture on a holistic basis.

One clear message that arises from one of the largest GM field experiments (**Figure 2**) is that the differences observed between crops are at least as great as, and in some cases larger than, the differences between treatments within a crop. This indicates that the longer-term impacts of the introduction of GM crops will be influenced by pressures which may change cropping patterns across landscapes. Drivers which lead to oilseed rape being more frequently grown as a break crop, for example, could benefit biodiversity, as this crop tends to support a much greater range of farmland wildlife. Basing decisions on a narrow comparison between the GM crop and its conventional counterpart ignores this greater context.

Meta-analysis of over 100 papers revealed that GMIR crops support a greater diversity of nontarget arthropods than conventional crops treated with insecticides, yet the comparison with the isogenic control can be in the other

TRENDS in Biotechnology

Figure 3 In bioremediation, plants and bacteria may work in consortia to degrade xenobiotics. Plants may take up the by-products of metabolism of bacteria, they may also selectively support indigenous degrading bacteria in their rhizosphere. Reproduced from Macek *et al.* (2008). With permission from Elsevier.

direction for a few specific nontarget groups. This raises the issue of which of these two comparisons is most appropriate for risk assessment. Currently, risk assessment emphasizes the comparison of the GM crop with its isogenic counterpart, yet it is the comparison with the conventional crop and its associated management regime that will most accurately reflect the impact of the crop if commercialized. Conventional practice may vary considerably from intensive practices to more extensive agricultural systems (e.g. across the EU), and therefore may need to be judged on a regional basis.

As a deeper understanding of the benefits and risks of GM crops have developed, it has become increasingly apparent that the treatment of conventional agricultural crops and practices is not consistent with the treatment of GM crops, and that this does not result in the best decisions for the environment or for future food security. New frameworks are required that allow the assessment of both environmental risks and benefits in a holistic sense, allowing decisions to be balanced, objective and based on all the appropriate information. An example of such a framework is a matrix-based approach called a comparative sustainability assessment (CSA) as developed by an advisory group to the UK government (ACRE, 2007). The proposed CSA contains 10 criteria of assessing sustainability, benefits and risks, none of which have precedence, and all of which need to be evaluated to come to a judgement. It will only be by employing this or other similar tools that policy makers will be able to come to fully informed decisions about which innovative crops or management techniques will help us meet targets for sustainable agriculture.

See also: Agricultural Production; Bioremediation; Fitness Costs of Plant Disease Resistance; Parasitoids; Plant Quantitative Traits; Plant Virus Transmission by Insects; Rhizosphere; Transgenic Plants

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