

Effects of biotechnology on biodiversity: herbicide-tolerant and insect-resistant GM crops

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Biodiversity is threatened by agriculture as a whole, and particularly also by traditional methods of agriculture. Knowledge-based agriculture, including GM crops, can reduce this threat in the future. The introduction of no-tillage practices, which are beneficial for soil fertility, has been encouraged by the rapid spread of herbicide-tolerant soybeans in the USA. The replacement of pesticides through Bt crops is advantageous for the non-target insect fauna in test-fields. The results of the British Farm Scale experiment are discussed. Biodiversity differences can mainly be referred to as differences in herbicide application management.

Loss of biodiversity through traditional agriculture

Loss of biodiversity is occurring in many parts of the globe, often at a rapid pace. It can be measured by loss of individual species, groups of species or decreases in numbers of individual organisms. In a given location, the loss will often reflect the degradation or destruction of a whole ecosystem. Recently, the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) (<http://www.biodiv.org/convention/sbstta.asp>) of the Convention on Biological Diversity ranked threats to global biodiversity as follows:

- (i) Habitat loss: probably the most serious of all threats to biodiversity.
- (ii) Introduction of exotic species.
- (iii) Flooding, lack of water, climate changes, salination and so on, all of which can be either natural or man-made.

The United Nations Environment Program (UNEP), in their 1997 Global State of the Environment report (<http://www.grida.no/geol/exsum/ex3.htm>), described regional environmental trends, which are remaining stable in most parts of Europe, but definitely getting worse in most developing countries. One positive exception is the lower land degradation rate in North America.

The unchecked rapid growth of human populations has had dramatic effects on biodiversity worldwide. Habitat loss owing to the expansion of human activities is identified as a major threat to 85% of all species described in the IUCN (World Conservation Union) Red List (<http://www.redlist.org/info/introduction.html>). Main

factors are urbanisation and the increase in cultivated land surfaces.

The shift from natural habitats towards agricultural land must have been dramatic in past times. The spread of wheat in Europe must have changed habitats and landscapes thoroughly and irreversibly over thousands of years [1].

Agriculture had far-reaching effects on human society, spreading across Eurasia and leading to increased populations and eventually to civilisations such as those of classical Greece and Rome. But most of this happened centuries before the invention of writing, so it is only through archaeology that we can understand prehistoric agriculture [2–4].

Today, more than half of humankind lives in urban areas, a figure predicted to increase to 60% by 2020 when Europe, Latin America and North America will have >80% of their population living in urban zones. Five thousand years ago, the amount of agricultural land in the world is believed to have been negligible. In 2000, arable and permanent cropland covered ~1497 million hectares of land, with 3477 million hectares of additional land classed as permanent pasture. The sum represents ~38% of the total available land surface (13 062 million hectares) [FAOSTAT Agriculture Data (<http://apps.fao.org/page/collections?subset=agriculture>)]. It seems that since 1997 the amount of arable land has not increased significantly. Those apparent limitations call for a change in agricultural strategies.

Habitat loss is of particular importance in regions of high biological diversity where food security and poverty alleviation are also key priorities (some parts of Latin America and Asia Pacific).

General impacts of modern intensive agriculture

Modern agricultural practices have been broadly linked to declines in biodiversity in agro-ecosystems. This has been found to be true for a wide variety of taxonomic groups, geographic regions and spatial scales. More specifically, various researchers have found significant correlations between reductions in biodiversity at various taxonomic levels and agricultural intensification. For example, a review of published studies on arthropod diversity in agricultural landscapes found species biodiversity to be higher in less intensely cultivated habitats [5]. Similarly, analysis of 30 years of monitoring records demonstrated

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that the abundance of aerial invertebrates at a location in rural Scotland was negatively correlated with a suite of agricultural variables that represent more intensive agriculture; that is, arthropod populations are lowest where agriculture is the most intensive [6]. In this same study, the abundance of various farmland bird species was, in turn, positively correlated with arthropod abundance in the same year and the previous year. Comparable studies have found similar impacts on bird species throughout the UK and European Union (EU). Across Europe, declines in farmland bird diversity are correlated with agricultural intensity and declines in the European Union have been greater than in non-Member States [7–9]. But arguments over biodiversity effects should not be allowed to be dominated by higher trophic levels such as birds because it is an anthropocentric value-judgment that invests these organisms with more importance than other species [9].

These effects of agricultural intensification undoubtedly highlight many contributing factors, which are addressed individually in the following sections, and include the cropping pattern, the frequency of tillage, the amount and nature of fertilizers used and the amount and nature of pesticides applied (particularly insecticides and herbicides). However, it should be noted that all of these factors are interrelated to a greater or lesser degree, often causing negative synergies [2,10]. There is no doubt that many human, social and cultural factors must be taken into account, but nevertheless, in all cultures it is uncontested that habitat conversion is acceptable to provide more food and settlement for our own needs. This is underlined by Dale *et al.* 'The kinds of potential impacts of GM crops fall into the classes familiar from the cultivation of non-GM crops (invasiveness, weediness, toxicity or biodiversity). It is likely, however, that the novelty of some of the products of GM crop improvement will present new challenges and perhaps opportunities to manage particular crops in creative ways' [11].

Impact of agricultural biotechnology on biodiversity

With the introduction of GM crops, concern has been raised that overall genetic diversity within crop species will decrease because breeding programs will concentrate on a smaller number of high value cultivars.

However, several studies have specifically focused on this subject and they have concluded that the introduction of transgenic cultivars in agriculture has not significantly affected levels of genetic diversity within crop species. For example Sneller *et al.* [12] looked at the genetic structure of the elite soybean population in North America, using coefficient of parentage (CP) analysis. The introduction of herbicide-tolerant cultivars with the Roundup Ready® [Monsanto (<http://www.monsanto.com/monsanto/layout/products/productivity/roundup/default.asp>)] trait was shown to have had little effect on soybean genetic diversity because of the widespread use of the trait in many breeding programs. Only 1% of the variation in CP among lines was related to differences between conventional and herbicide-tolerant lines, whereas 19% of the variation among northern lines and 14% of the variation among southern lines was related to differences among the lines

from different companies and breeding programs. Similarly, when Bowman *et al.* [13] examined genetic uniformity among cotton varieties in the USA, they found that genetic uniformity had not changed significantly with the introduction of transgenic cotton cultivars. Genetic uniformity actually decreased by 28% over the period of introduction of transgenic cultivars. In light of those data theoretical concepts of Gepts *et al.* [14], stating that GM crops should be held responsible for a biodiversity decline within crops, are not very convincing. It remains to be said that the continued use of locally adapted traits gained in traditional breeding should have a more important role than it does at present [15].

In conclusion, biotechnology represents a tool for enhancing genetic diversity in crop species through the introduction of novel genes. This does not aim at the single transgene inserted, but is based on the fact that beneficial characters can now be inserted in a variety of crops that have been neglected because of the limitations of traditional breeding methods, which failed to enhance the traits. There is great potential to achieve drought tolerance in vegetables [16] and to avoid post-harvest losses in African grain staple crops [17].

Selected case studies

Application of conservation tillage easier with herbicide-tolerant crops

The soil in a given geographical area has had an important role in determining agricultural practices since the time of the origin of agriculture in the Fertile Crescent of the Middle East. Soil is a precious and finite resource. Soil composition, texture, nutrient levels, acidity, alkalinity and salinity are all determinants of productivity. Agricultural practices can lead to soil degradation and the loss of the ability of a soil to produce crops. Examples of soil degradation include erosion, salinization, nutrient loss and biological deterioration. It has been estimated that 67% of the world's agricultural soils have been degraded [18]. It is also worth noting that soil fertility is a renewable resource and soil fertility can often be restored by several years of careful crop management.

In many parts of the developed and the developing world tillage of soil is still an essential tool for the control of weeds. Unfortunately, tillage practices can lead to soil degradation by causing erosion, reducing soil quality and harming biological diversity. Tillage systems can be classified according to how much crop residue is left on the soil surface [19–21]. Conservation tillage is defined as any tillage and planting system that covers >30% of the soil surface with crop residue, after planting, to reduce soil erosion by water [19]. The value of reducing tillage has been recognized for some time but the level of weed control a farmer required was viewed as a deterrent for adopting conservation tillage. Once effective herbicides were introduced in the latter half of the 20th century, farmers were able to reduce their dependence on tillage. The development of crop varieties tolerant to herbicides has provided new tools and practices for controlling weeds and has accelerated the adoption of conservation tillage practices and 'no-till' practices [19]. Herbicide-tolerant cotton has been adopted rapidly since its introduction in 1997 [20]. In

the USA, 80% of growers are making fewer tillage passes and 75% are leaving more crop residue [National Cotton Council of America (<http://www.cotton.org>)]. In a farmer survey, 71% of the growers responded that herbicide-tolerant cotton had the greatest impact on soil fertility related to the adoption of reduced tillage or no-till practices. In soybean, the growers of glyphosate-tolerant soybean plant a higher percentage of their acreage using no-till or reduced tillage practices than growers of conventional soybeans. 58% of glyphosate-tolerant soybean users reported making fewer tillage passes than they did five years ago compared with only 20% of non-glyphosate-tolerant soybean users. 54% of growers cited the introduction of glyphosate-tolerant soybeans as the factor that had the greatest impact toward the adoption of reduced tillage or no-till methods [American Soybean Association (<http://www.asa-europe.org/>)].

The case of Bt toxins negatively affecting non-target insects

The use of GM crops can positively impact agricultural species biodiversity if the GM crops enable the management of weeds and insect pests in a more specific way than chemical herbicides and pesticides. In particular, the adoption of insect-resistant Bt crops, expressing highly specific Bt proteins, represents an opportunity to replace broad-spectrum insecticide use. The insecticidal proteins expressed in Bt crops such as Bt maize and Bt cotton are so narrow in their activity that they have little or no activity against non-target organisms. Furthermore, the toxins are expressed within the plant tissues, minimizing the exposure of animals that do not feed on the crop plants. As a consequence, considering the large number of field studies that have been conducted, few or no differences have been seen with respect to community structure or individual species abundances where fields of Bt crops have been compared with conventional crops that have not been treated with insecticides. Where they have been calculated, indices of species diversity and community structure have not differed significantly for Bt corn fields compared with untreated conventional corn fields (e.g. [22–24]) or for Bt cotton fields compared with conventional cotton fields [25–28]. The only species that have been observed to be significantly and consistently less abundant in fields of Bt crops compared with conventional fields are the target pests and their specific parasites. In studies where the conventional crop fields have been sprayed for the target pest species of the Bt crop (as it routinely occurs in most crop systems) many non-target species have been observed to be adversely impacted, leading to significantly lower non-target populations in sprayed conventional fields compared with Bt crop fields. With corn fields, this is particularly obvious for foliage-dwelling species because of the method of application of these insecticides, but ground-dwelling species like carabids and cursorial spiders are also often affected, directly or indirectly, by insecticidal sprays and are apparently not affected by Bt corn [24,29]. The study by Candolfi and colleagues was particularly impressive (Figure 1).

Similarly, a variety of studies of Bt cotton in the USA, Australia and China have all demonstrated that

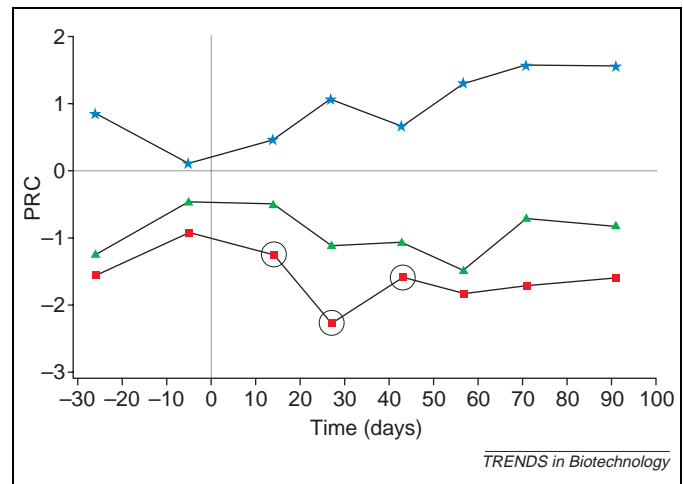


Figure 1. Principal response curve (PRC) analysis for soil-dwelling organisms. The zero line of the y-axis represents untransformed corn (control). Bt-corn is shown as blue stars, untransformed corn treated with Delfin is shown as green triangles and untransformed corn treated with Karate Xpress is shown as red squares. Day 0 was the spray day. Statistically significant treatment effects when compared with control are circled (goodness of fit $R^2_{/0.74}$, goodness of prediction Cross-validation/Jackknife $R^2_{/0.62}$). Reproduced, with permission, from [29].

populations of many non-target species are higher in Bt cotton fields than in sprayed conventional cotton fields [25,26,28,30]. Likewise, work on potato fields in the north-eastern USA has revealed larger populations of many generalist predators in Bt potato fields than in conventional potato fields treated with appropriate broad-spectrum insecticides [31]. In contrast to Newleaf potatoes and microbial Bt formulations, however, the broad-spectrum insecticide, permethrin, had much broader and more severe unintended impacts on non-target arthropods. Debates over potential environmental risks associated with large-scale use of transgenic Bt crops have been based largely on philosophical arguments, conjectural ecological theories and laboratory studies [32], which give important hints on how to deal with toxic effects in the food web. Two new papers show results that correlate well with the above-mentioned field studies [33–35].

The case of the monarch larvae in Bt cornfields

The controversy surrounding the fate of Monarch butterfly larvae in US Bt cornfields seems to be solved. Losey's publication [36] revealed that the Bt protein built in transgenic corn resulted in toxic effects to the Monarch larvae, and triggered a worldwide protest against GM crops. Later, extensive field work demonstrated no significant impact of the Bt protein on Monarch larvae [28,37–49]. Parallel to this, results from laboratory experiments on forced-fed predators such as lacewing larvae showed significant impact of the Bt toxin. Recently, further laboratory work on the same predator under more-realistic conditions did not yield the same results, and in fact the lacewing larvae remained healthy. Romeis *et al.* [50] explained this discrepancy by the fact that prey fed to the larvae was fully vital in contrast to prey affected by Bt toxin in the previous experiments [32,51]. Note that it was Rachel Carson herself who named Bt proteins as a possible way out of the pesticide crisis, which she described in her famous 'The Silent Spring', and one can

only wonder what she would have said about the Bt toxin built genetically into the corn-borer-infested crops instead of being sprayed in large, but rapidly decomposing, quantities [52].

The case of the British farm-scale experiments

Highly publicised even before it started, the results of the three-year-long experiment on three genetically modified herbicide-tolerant (GMHT) crops over >200 fields in Great Britain have had a great impact in the press and therefore on the public [53–64] (See also the critical assessment by [65]). The well intended experiments yield significant amounts of data related to herbicide and crop management differences and these were rigorously collected and duly peer reviewed.

The results can be summarized as follows: differences in biodiversity between crops exceed differences between GMHT and conventional crops [56,57,60–63]. There were higher early season weed numbers and biomass in all three GMHT crops [57] and higher weed mortality in GMHT sugar beet and canola resulting in lower late-season biomass and seed rain of weeds in those crops, but lower weed mortality in GM maize [57]. More detritivores (collembola) were observed in all three GMHT crops as a result of higher weed detritus [60,61]. There were lower numbers of bees, butterflies and Heteroptera in GMHT sugar beet and canola were observed as a result of reduced weed populations; generally higher numbers of invertebrates in GM maize [60,61]. Lower herbicide inputs in GMHT crops [58]. It has been argued that GM maize is performing better because it has been treated with the broad-band herbicide atrazine, but [66] showed with a more detailed analysis of data from the trials that this is not the case: GM maize resulted in more weeds than conventional maize, even when treated with non-atrazine herbicides (Figure 2).

The GMHT crops have been planted in Great Britain for the first time and farmers actually have not been experienced enough to apply advanced techniques such as no tillage, which would have then given the full advantages of the method. It is quite logical and has never been contested that the application of a broad band herbicide such as Roundup Ready® would be efficient in killing weeds, and as a consequence the biodiversity within the fields is reduced and has various consequences, which have been studied in detail. The farm-scale studies could be summed up in a simple message: no weeds → no insects and → no weed seed. In turn, no insects and no weed seed → no bird food. No bird food → no birds. However, it is not this simple; first of all we must realize that we are not dealing with natural habitats and even the sky larch is an artificial product of agriculture. We are therefore dealing with highly dynamic ecosystems and have many opportunities for improvement. Relatively minor change could bring back biodiversity to the fields by applying the appropriate methods. The Farm Scale Experiments (FSE) fail to take into account that management methods have changed in the USA with the advent of GM crops. Experimental outlays in field research must take into account the full potential of management in modern farming, such as no tillage methods. Even seen as a true management

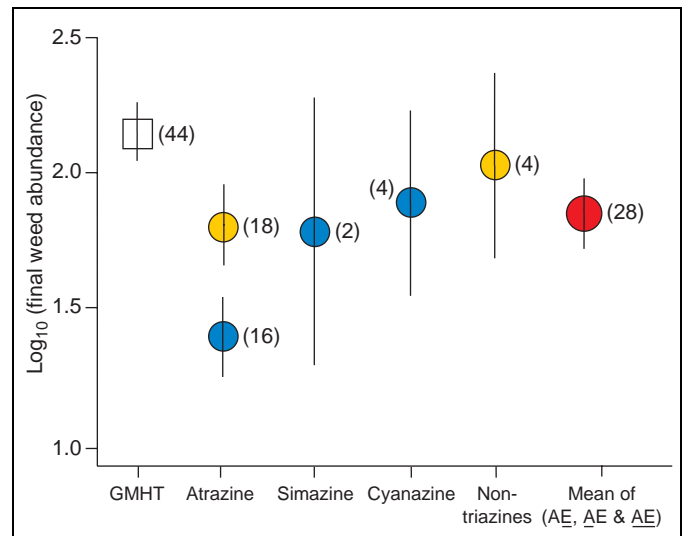


Figure 2. Mean abundance of total pre-harvest weeds and herbicide use. Consistent treatment effects (from Table 2 in [76]), illustrated here by mean abundance of total pre-harvest weeds in FSE fodder-maize per GMHT (square) or conventional (circles) half-fields, and treated either with atrazine (A) or without atrazine (Δ), under regimes that included either pre-emergence herbicide plus possible post-emergence application(s) (blue circles, E) or post-emergence herbicide only (yellow circles, \bar{E}). The red circle represents the mean of the three conventional regimes \bar{AE} , ΔE and \bar{AE} ; that is, all those other than atrazine applied pre-emergence. Numbers in brackets denote N, the number of half-fields. Bars represent the 95% confidence interval for each mean. Reproduced, with permission, from [66] (<http://www.nature.com/>).

experiment it is not done in a full farm scale manner: it fails to compare yield and other input-output data to residue analysis of conventional herbicides within the non-GM crop fields. It would have been possible to apply standard methods used in integrated pesticide management systems such as the Cornell Environmental Impact Equation [67–69]. The following is just one example (out of the overall comments of one of the author groups of the FSE [59]). When, in the USA, large areas of crops were replaced by GMHT varieties, the profile of agrochemical inputs on the farm changed, the proportion of the land that was tilled before sowing sometimes decreased, less chemicals were lost in leachates and run-off from the field, and, as glyphosate and glufosinate ammonium are relatively short-lived and of low toxicity to animals, the change in profile was considered to lessen the wider impact of farming [70,71]. The chain of impacts was not the same for all crop species, and generalizations are difficult [70,72].

A caveat to acknowledge is that the soils in the UK are not similar to those in the USA and this might reduce the potential benefits of no tillage strategies, a problem that should be tackled on an experimental basis.

If all the FSE data were available and a better-adapted management had been applied, results would not look so bleak for the Roundup Ready® technology. Data from Romania have shown that economically it is indeed rewarding to use the Roundup Ready® technology [73]. Overall, with the flexibility and simplicity of the herbicide-tolerant crop method it should be easier to make progress (which has its limits there, where farmers do not like weed components in the harvest because there are several problematic toxicity cases known to be connected to certain species of weeds [74,75]). With the incentive of the economic advantage farmers will agree more easily to

do something extra for agricultural biodiversity to enhance conservation in arable fields. See also the chapters on (no-) tillage and pesticide use in [76,77]. It will be rewarding to see the data of the FSE explored by more researchers because the authors have opened the datasets to the scientific community, a laudable move by the Farm Scale research coordinators. Statisticians should have a closer look at variation, dynamics and individual treatments. Some of those treatments could well reveal key data on how to enhance successfully biodiversity in fields with GMHT crops. It is understandable, that in a first round of experiments researchers have concentrated on the big question of comparing the two technologies as a whole and also with sound statistics of average values – average values that could have been achieved with smaller data packages, which often bury the subtle details from which we could learn more. Having a closer look at variation related to the individual management methods would probably also have the potential to suggest future strategies, but this exploration might be limited by the high amount of noise and variability in the system. As a whole, we encounter the same phenomenon often seen in scientific controversies on complex ecological issues, the FSE controversy is no exception. As a reader it is easy to lose sight and to pick out the data that fit to your own view in a reductionist manner; it is more difficult to keep an open mind and to analyze agricultural issues on biotechnology and biodiversity with a truly holistic approach. Chassy *et al.* comment that one important question has not been asked yet [78,79]: Which agricultural technologies will maximize production while minimizing environmental impact in the broad sense? The future of agricultural research in finding better strategies and management systems will be most effectively developed if we throw off the constraints of our monofocal view on GM technology, and use the approach to address other land-management issues. Such experiments must be designed and resourced at the appropriate scale so that we can adequately address these major practical questions [10]. After all, there are no scientific constraints stopping development of transgenic crops for organic farming. In this regard rewarding approaches in research with sugar beet management are published by Dewar *et al.* [80–82].

Conclusions

Preservation of the genetic diversity present in crop species is an important need being addressed by various public and private programs. In this respect, biotechnology can be a valuable tool for introducing novel (alien or non-alien) genes into underused crop traits and crop species. Furthermore, the development and introduction of GM crop varieties does not represent any greater risk to crop genetic diversity than the breeding programs associated with conventional agriculture. After all, the overall performance of a plant and the quality and quantity of its product is the result of thousands of genes and the genetic background is almost always more important for the questions dealt with in this review than a single transgene.

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