



Does the use of transgenic plants diminish or promote biodiversity?

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The protection of biodiversity and of ecosystem services ought to be a top priority, taken into consideration in the course of all human activities, because we depend on it fully now and for the future. In this context, we note that the ecological problems related to the cultivation of GE crops fail to differ in any fundamental way from the ecological problems associated with agriculture in general, except that they usually involve the application of much lower quantities of chemicals and thus tend to leave the environments in and adjacent to where they are grown in better condition than do the conventional ones. Higher productivity on cultivated lands, which is one outcome of growing GE crops, protects biodiversity by sparing lands not intensively cultivated, whereas relatively non-productive agriculture practised is highly destructive to biodiversity, since it consumes more land in an often destructive way, even though more biodiversity may be preserved among the crops themselves than in industrialized, large fields, especially if hedgerows and woodlands are not encouraged in near proximity. The major preservation of biodiversity, however, does not take place among crops! If weeds are present that are closely related to the crops, they may acquire immunity to the effects from which the crops were protected and be more difficult to control among them. The production of superweeds as a result of hybridization between cultivated crops and their wild relatives is essentially a myth. The definition of 'organic' production in the U.S. and elsewhere unjustifiably rules out GE crops, often in such a way as to damage the environment more than would be the case otherwise. Unless the definition of 'organic' is a problem, or close relatives to the crops are weedy among them, there seems to be essentially no ecological risk involved in growing GE crops.

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For reasons that remain somewhat obscure, several institutions and well-intentioned individuals continue to oppose the use of contemporary genetic techniques to enhance the properties of crops. There is no scientific evidence that the process of transferring genes from one kind of organism to another poses intrinsic problems. Further, not a single one of the hundreds of millions of people who regularly consume foods produced by GE plants has become ill as a result of eating such foods. As I will review now, the ecological problems often supposed to be related to the cultivation of such crops do not differ in any fundamental way from the ecological problems associated with agriculture in general. Notwithstanding the evidence, all of these points continue to be cited as reasons that it supposedly problematical to grow crops with features that have resulted in part from the application of these particular methods.

Here we are concerned with direct and indirect effects of cultivating GM crops on biodiversity. The preservation of biodiversity is of major importance to human beings and to our prospects for the future. Our ancestors evolved as one of millions of species on earth and we are entirely dependent on biodiversity for our existence here. All of our food comes directly or indirectly from plants. Plants provide all of the medicines used by a large majority of the people on earth and a large fraction of prescription drugs came originally or still come from organisms. In communities and ecosystems, the relationships between organisms preserve topsoil, regulate the run off of water, and often determine local climates. The beauty of organisms supports us and uplifts our spirits, inspires our art and fills our days with delight.

During the half century in which we have enlarged our understanding of the functioning of genes and molecules, it has become evident, as Dick Flavell emphasized, that our hopes for the future rest, in large part, on our ability to understand and to utilize the properties of biodiversity wisely. Our level of understanding now is very poor. Of the estimated 12 million or more species of organisms other than bacteria or viruses, we have so far named 1.7 million and we know next to nothing about the great majority of these. We are naming approximately 10,000 additional species a year, so that it would take us more than a century to give names to those we believe exist now. That will not be possible, however, because of the rate at which species are disappearing. Comparing rates of extinction that can be measured in the fossil record with those estimated to be occurring now, we can state that the rate of disappearance of species has risen over the past 10,000 years, and especially recently, from about 1 species per million per year to at least hundreds of species per million per year.

At that rate, and considering the progressive destruction of habitat, the spread of invasive species in natural habitats and the loss of habitat to global warming, as many as two-thirds of all species in existence now could disappear within the course of this century. That would be a loss comparable to the one that occurred 65 million years ago, at the close of the Cretaceous Period. At that time, the nature of life on earth changed fundamentally and the tempo of evolution was not recovered for an estimated 10 million years. For us, it would mean an enormous loss of our capacity to benefit from the properties of those organisms and an impoverished, less sustainable, and less healthy earth. To ignore the loss we are causing is truly unwise from any perspective. The great American conservationist Aldo Leopold put it this way:

'The first rule of intelligent tinkering is to save all the cogs and wheels.'

What is the role of GE crops in driving the extinction of life at such frightening rates? Plainly, the spread of agriculture itself over the past 10,500 years has greatly lowered the survival rate for local biodiversity and of the world's biodiversity as a whole. A major effort is made in cultivated fields to exclude all organisms except for the one being grown. Exceptions are, of course, made for pollinating insects and some other beneficial forms, but the principle remains generally true. It is obvious that cultivating crops over an estimated 11% of the earth's land surface limits the extent of biodiversity both locally and generally. Considerations of the effects of GE crops on biodiversity must begin with an understanding of this relationship. Providing food for a rapidly increasing human population, currently estimated at 6.8 billion, has led to the elimination of a large fraction of the world's biodiversity over the past 10,500 years, as the human population increased and agriculture spread and intensified. When crops were first domesticated, the entire human population amounted to several million people, a number that has grown over approximately 400 generations (10,500 years) to its present level. As this rapid growth has taken place, the lowlands of tropical, subtropical and temperate regions have been stripped of more than half of their original vegetation, the remaining natural habitats often persisting only in relatively small patches.

With the exception of the agroforestry systems developed in recent decades, we may say that the more intensive the agriculture, the fewer weeds persist in cultivated fields; this in turn results in reductions in the populations of insects, birds and other animals that feed on the weeds or on the cultivated plants themselves. Traditional small fields may include more biodiversity than large, industrial-scale ones, because they are likely to fit into the natural landscape better and to be less intensively cultivated. The biodiversity that remains in a large field of hybrid maize or a rice paddy is limited, even though the crops in these cases are not products of genetic engineering. Agricultural fields have been increasing in size and intensity of cultivation for centuries, with the inevitable result that transgenic technologies are particularly useful there, although their use is in fact size neutral with respect to the fields. The effects of agriculture, often including the use of a high proportion of the regionally available water or the application of large amounts of pesticides or herbicides that drift regularly into the surrounding ecosystems, are profound and can be devastating [1]. When GE crops are grown, some of these negative effects can be avoided or ameliorated because of the particular characteristics of the GE crops (e.g. [2]). Are there also specific negative effects of the cultivation of GE crops on the environment? In the following, we shall review and evaluate the suggestions along these lines that have been offered by various authors.

Modern agriculture is more efficient and much more highly productive than earlier kinds of agriculture, which would not have been adequate to support the numbers of people that now inhabit the Earth. Milpas sprawling over the hillsides of southern Mexico have low yields of maize, but they also incorporate many other useful and medicinal plants. If human populations remain low, such methods of cultivation serve them well; as the population grows, the kind of production levels attained in the large fields of northern Mexico are necessary to keep pace with the need to feed

the higher numbers of people. Overall, the level of maize production in Mexico is insufficient to supply the amounts necessary for domestic consumption; the situation can be alleviated only by achieving increased productivity, but the conservative agricultural practices that are prevalent in various regions of the country have made it difficult to achieve an adequate yield.

Historically, agricultural improvements have tended to spread rapidly. When hybrid maize was planted on hundreds of thousands of acres in the central U.S. starting in the 1930s, few understood the principles of hybrid vigor or the double-cross method of producing the maize; yet there was relatively little objection to the large, high-yielding fields that resulted from this technical advance and a great deal of pleasure with the results. Clearly, the lower-yielding maize fields that existed up to that time had held more weeds and hence more biodiversity, but that was seen as an undesirable situation, holding back the implementation of a new kind of highly productive agriculture. Times change, and the degree of difficulty in achieving public acceptance of GE technology could not have been imagined a few decades ago.

Central to lessening the impact of agriculture on biodiversity is the way the bordering lands, roadsides, hedgerows, patches of woods, relict prairies and other natural communities persisting among the agricultural lands are managed. As mentioned above, and for example, herbicides drifting from the fields sometimes have very negative effects on the health of native vegetation, and pesticides may kill very large numbers of other organisms in the surroundings of the fields. There is ample evidence that maintaining a sort of overall balance in the countryside helps to support ecological services, such as those provided by healthy populations of predators (birds, insects, other animals that help control crop pests), as well as pollinators that visit the flowers of many crops and help to insure good seed set. Weeds may spread from the fields into neighboring habitats with results damaging to biodiversity, a topic to which we shall return.

The overall genetic diversity of the maize crops grown in the United States and eventually elsewhere was clearly decreased by the widespread planting of hybrid corn, but the insertion of transgenes to enhance the characteristics of particular crops is scale-neutral. Thus more than 700 varieties of soybeans grown in the United States have been made glyphosate resistant and the overall number of different strains grown is no different than it was before the more efficient methods of cultivation involving GE strains were developed. Similarly, the deployment of individual strains of hybrid corn, which does not involve the precise transfer of individual genes, means that many original parents are used to produce the strains that have the highest yields in particular, relatively small, regions. In short, the application of GE technology to the improvement of crops does not, in itself, limit the overall diversity of the crops, whereas the development of modern agriculture, in which certain genetically defined strains are grown over wide areas and other strains that were cultivated locally earlier may disappear, does. The preservation of genetic diversity in crops is important and of general interest, but the appearance of GE crops did not cause the problem or advance its spread.

A very limited amount of additional arable land is available for the spread of crop agriculture. It is of the utmost importance that the land cultivated now be utilized in the best possible way; doing so will do a great deal to protect biodiversity by preventing further

incursions into formerly undisturbed habitats. To attempt a switch to the less productive forms of organic agriculture worldwide would, in this sense, be a tragic mistake, leading to the destruction of large areas where species survival would suffer greatly as a result. A special word about biofuels is in order at this point. If they can be cultivated in marginal lands not now cultivated, biodiversity will suffer greatly; if lands are taken out of conservation reserves to cultivate biofuels, biodiversity will again suffer greatly. Producing ethanol seems to require more energy than it generates, and while biofuels of some kind will clearly be a part of our future energy budgets, we must plan for it carefully and in view of the potential for further destruction of life.

Aside from the environmental effects of chemicals used in connection with growing GE crops, which we will treat subsequently, or the possible effects of toxins or other chemicals produced within crop species when the plants decay, also to be treated subsequently, the possible effects of GE crops on biodiversity include the following categories: (a) gene flow to weedy or wild relatives; (b) the transfer of genes from the GE crop to non-GE crops of the same species; (c) the possible production of new, aggressive weeds as a result of hybridization between the GE crop and wild or weedy relatives; (d) the effects of the chemicals produced by certain GE plants on non-target species. Each of these will be discussed in with respect to the probability of the events and the effects that might follow their occurrence.

Gene flow to wild or weedy relatives of crops

Gene flow between crops and their wild or weedy relatives has been a constant feature of agriculture ever since people began to cultivate plants. As many authors, starting especially with Edgar Anderson, have documented, hybridization of this kind has had a major role in enhancing the genetic variability of both the crops, facilitating the selection of suites of desired characteristics, and of their weedy or wild relatives. In some cases, as for example in the origin of hexaploid ($2n = 42$) bread wheat (*Triticum aestivum*), the hybridization has been followed by polyploidization, stabilizing the hybrid and its characteristics as an object for further selection through selective planting in the mixed fields. In others, as in the origin of maize (*Zea mays*), repeated backcrossing and selection of plants with improved characteristics from wild relatives, teosintes, has facilitated the assembly of the characteristics of modern maize over a period of perhaps 7000 years in southern Mexico. There are no naturally occurring plants that resemble either bread wheat or maize, and of course bread wheat can form fertile hybrids only with other hexaploids. Maize, by contrast, can hybridize with teosintes that have the same chromosome number ($2n = 20$) and the characteristics of the wild and cultivated plants can be recombined in different ways both in the crops and in their wild relatives. The diversity of local strains, land races, of maize in Mexico and elsewhere has a great deal to do with the recombination of these features following hybridization of the sort discussed.

The two examples just reviewed have parallels in the origin and subsequent improvement of virtually all cultivated crops; therefore, it should not be surprising that GE crops hybridize in the same way and to the same degree as takes place in the evolution of all other crops, reviews by Ellstrand and CAST [3,4]. When hybrid maize and other improved varieties were introduced into Mexican fields, their characteristics spread widely and were used by the

indigenous people for developing improved local strains. The diversity of races of maize that occurs across Mexico and elsewhere is continually evolving in a way one could imagine as the patterns in a kaleidoscope, with repeated inventories separated by decades yielding strikingly different results as a result of the continued selection and introduction of new forms into the specific areas. What the introduction of GE corn plants into the region would mean environmentally would depend on the particular characteristics of the genes involved and the selective forces encountered in different regions.

Considering maize or any other crop in context, and taking the main genes that are widespread in certain crops – Bt protection from pests; glyphosate-ready crops; and virus resistance – we may first ask what the consequences of these genes reaching wild or weedy relatives might be. If the weeds or wild plants gained Bt protection from their pests, and if the pests generated significant selective pressures in the particular environment, the genes might persist in the wild or weedy populations. If they did persist, the plants would be better protected from the pests that were attacking their cultivated relatives than they would be otherwise. A concrete example of the movement of a Bt transgene from cultivated to wild sunflowers (*Helianthus annuus*) reducing herbivory and increasing fecundity in wild populations of the same species is provided by Snow *et al.* [5] and Poppy and Wilkinson [6]. It is difficult to imagine why the acquisition of enhanced protection from herbivores by wild or weeds plant populations would pose an environmental problem and we are not aware of any demonstration that that would be the case.

The question of herbicide resistance is more complex. Whenever herbicides are used in agriculture, resistant strains of the target species and other species that are regularly exposed to the herbicides will eventually appear. For example, the widespread use of glyphosate has resulted in the appearance of several resistant strains of weeds in different areas. This is a general property of herbicide (or pesticide) use and in principle has nothing specifically to do with whether GE crops are the ones treated or not. Various strategies have been employed to deal with herbicide-resistant weeds, similar to the strategies used for dealing with antibiotic resistance in human beings or other animals; and they will continue to be needed in agricultural situations whether or not GE plants are involved.

In the case of bentgrass *Agrostis stolonifera*, glyphosate-resistant strains appeared up to 21 km from the plots where the GE plants were cultivated, although most of the gene flow took place within 2 km [7]. This is considered a problem in the sense that glyphosate is the principal means of controlling this introduced European grass, grown as turf but weedy for example in clearings in forests and parks. This example also demonstrates the fact that the mode of pollen dispersal greatly affects the effects of growing GE crops, or any cultivated crops, at certain distances from their wild or weedy relatives. Clearly alternative herbicides could be found for such infestations, but the advantages and disadvantages of planting glyphosate-resistant turf need to be considered on their own merits in the context of the environmental situation overall.

These examples illustrate some of the diverse situations that can arise with the transgenes that are currently in widespread use. As additional genes are introduced in various crops, they should be

evaluated for their possible effects if they were transferred into wild or weedy relatives. In general, though, there appears to be no reason to fear gene flow from GE plants generally. In addition, most crops are not grown in areas where their wild relatives occur, so there is often no possibility for gene transfer. Only in Mexico and Guatemala, for example, are there wild relatives of maize with which the crop could hybridize; there is no possibility of gene flow elsewhere. Within the borders of the U.S., the only cultivated crops that have wild relatives with which they could hybridize are blueberries, sunflowers, some squashes, and pecans; for all other crops there is by definition no possibility of GE traits spreading to wild relatives. For some cultivated species, such as *A. stolonifera*, mustards (*Brassica*), radishes (*Raphanus*), and lettuce (*Lactuca*), however, there are introduced weedy relatives in the U.S. If these weeds grow with the related crops, they may acquire, for example, herbicide resistance from them. In Europe, the acquisition of herbicide resistance by weedy beets (*Beta vulgaris*) within fields of sugar beets, a specialized strain of the wild species, is a matter of concern because of the added difficulty in controlling the herbicide-resistant weeds with the crop fields. Clearly, every situation must be dealt with by appropriate agronomic practices, as would be the case even if GE traits were not involved.

Transfer of genes between GE and non-GE crops of the same species

A second area of concern has to do with the transfer of genes from GE crops of a given species and other non-GE crops of that species. The problem here arises to a large extent because of the classification of GE crops as ‘non-organic’ by the U.S. Department of Agriculture, which in turn drives a concern about their ‘purity’, a strange notion given the ways in which plants actually evolve. We see no logic in this designation, which basically puts an additional obstacle in the way of attempts to achieve sustainable agriculture, and I particularly would like to endorse the suggestion made here by M.S. Swaminathan that these two approaches to agriculture be brought together to accelerate the improvement of desirable characteristics of crops. As I emphasized earlier, agriculture itself is unnatural and all cultivated plants and domesticated animals have characteristics that they have acquired over the years as a result of genetic manipulation. In the context of a world that so badly needs increased food production, it seems unwise in the extreme to rule out modern, precise methods of crop improvement on ideological grounds.

In general, there will be transfer between different kinds of crops of any given species, provided that the plants are outcrossing. The distance over which such transfers will occur depends on the way that pollen is transferred in the individual crop species. For plants in which the pollen is transported by the wind, such as walnuts, poplars, pines or grasses, the distances the pollen may move may be relatively great. In outcrossing grasses such as maize and sorghum, for example, the wind may, as we have seen for *A. stolonifera*, carry pollen over tens of kilometers to a receptive stigma under certain circumstances and result in the appearance of GE or other traits far from the place where crops with those traits are grown. In some crop plants, such as rice, wheat, barley and soybeans, self-pollination is the rule and only a very small proportion of the pollen is shed and dispersed by the wind. For many other crops, such as apples, potatoes, canola, squashes, alfalfa,

lettuce, sunflower, fruit trees and berry crops, the pollen is transferred by insects and the distances the pollen regularly travels will depend on the nature, abundance and habits of the individual pollinating insects and the characteristics of the flowers they visit.

As in the previous discussion, and leaving aside the legal designation of GE crops as 'non-organic', the effects of such transfer will depend on the nature of the genes involved, and the persistence of these genes will in turn depend on the selective pressures to which the plants with the new genes are subjected. Given the genes that are now used on a wide scale in producing GE crops, the recipient crops may be resistant to particular herbicides, less vulnerable to attack by pests, or resistant to plant diseases. One can easily see the ways in which the genes associated with these characteristics would increase or decrease under various selective regimes. In general, it is not obvious why any of the possible outcomes should be a matter of concern regardless of the degree of gene transfer that may occur in particular situations.

Production of new weeds

Some 20,000 plants are regarded as weeds, spreading in natural or artificial situations somewhere in the world. Those that grow among crops negatively affect their yields. The great majority of weed species were originally introduced by people from one place to another, often deliberately, and in connection with agriculture or horticulture. Other weeds have moved accidentally, contaminating or adhering to some product or object that is itself transported. One of the arguments used against planting GE crops is that in some way they might give rise to new, particularly aggressive weeds that would otherwise not occur. There are in fact a few examples of the origin of important new weeds involving crops, notably Johnson grass (*Sorghum halepense*) and weedy red rice, which originated as a hybrid between cultivated rice, *Oryza sativa*, and its progenitor species, *O. rufipogon*. Both of these weeds pose serious agronomic problems because they have characteristics similar to those of the crops from which they were derived and thus are particularly difficult to control. Neither of these cases, however, involves GE technology.

By contrast, the movement of genes for resistance to pests or herbicides from the crops into particular weeds, which I discussed earlier, certainly adds to the difficulty of controlling these weeds in the cultivated fields. Thus, wild beets (*Beta vulgaris*) that have acquired herbicide resistance are important weeds in the fields where a domesticated strain of the same species, the sugar beet, is grown; a modest number of similar examples are known. One should, however, view this problem in the context of the thousands of known aggressive weeds and deal with it on a case-by-case basis. As many have pointed out, the characteristics of weeds are very different from those of most cultivated plants, and many crops – maize and soybeans being good examples – never establish themselves in nature and rarely even re-seed in cultivation, so that their possible contribution to the formation of new weeds is particularly difficult to imagine.

Effects on non-target species

Particularly with respect to those GE plants that manufacture Bt toxin, it has at times been claimed that non-target species could be endangered. The case of the monarch butterfly (*Danaus plexippus*) in North America provides an illustrative example. It was claimed,

on the basis of laboratory experiments, that Bt toxin engineered into maize was expressed in such large quantities in the maize pollen that it could, when shed, coat milkweed plants (*Asclepiadaceae*), the food plants of monarch caterpillars, so thickly that it would poison them. In fact, such a thick coating of pollen virtually never occurs in nature and all maize strains used currently have been engineered so that Bt toxin is not produced in the pollen; so that there is actually no problem. In another case, it was claimed, on the basis of faulty laboratory data, that Bt toxin from residual plant material was poisoning caddis fly larvae (*Trichoptera*) in streams near the maize fields; such effects simply do not hold for the concentrations of the toxin that could occur in such streams.

All such effects need to be weighed against the effects on the environment of alternative agricultural practices not involving GE plants. In Europe, for example, where applications of pesticides and herbicides are much higher than those used in the U.S., human and environmental health are clearly compromised to a degree that would not be true if GE crops were grown widely, avoiding the use of such large amounts of chemicals in the environment. When Bt toxin is produced by bacteria grown in vats, killed and ground up, it can by the rules of 'organic' agriculture be spread in vast quantities over fields and forests, with the resulting death of a large proportion of all species of moths, butterflies and caddis flies in the environment. In contrast, when Bt toxin is produced internally by GE plants, only those herbivores that actually feed on these plants are affected. The former situation would be ruled 'organic', the latter 'non-organic', which we consider to be a strange application of logic. It must however be added that for herbivores feeding on GE plants producing Bt toxin, their exposure to the toxin and therefore their chances of developing resistance to it are presumed higher than in those species periodically subjected to 'blasts' of the pesticide.

In many tests, invertebrates have been found to be much more abundant and diverse in agricultural fields where GE crops were being grown than in those subjected to the continual application of pesticides, not a surprising outcome. On cotton fields in the Southeastern U.S., for example, more than 20 applications of pesticides per crop have conventionally been applied, with obvious and directly traceable environmental effects. Other crops are even more highly doused in poisons, especially in Europe, where the chemical industry sells much higher amounts of pesticides and herbicides than in the U.S. In view of these considerations, it is understandable why such a high proportion of the cotton cultivated throughout the world has been engineered to produce Bt toxin, with higher yields and improved human health a characteristic outcome. Why many Europeans should have chosen to live in unhealthy, highly polluted environments rather than use the new, much cleaner technologies remains a mystery to me.

Legalities

Having been involved personally in the formation of the Convention on Biological Diversity in the 1980s, I am truly saddened by the fact that it has become so preoccupied with GE crops. The so-called principle of 'biosafety' is not based on any valid scientific principles, and working it up through the Cartagena Protocol and by other means has given license to those who for personal

reasons, presumably of a political nature, wish to vent their spleen. This unwise and wasteful procedure has consumed thousands of hours of time by hundreds of diplomats and idealists, and not produced any result of the slightest use for the preservation of the world's biodiversity, which we all hoped would be the outcome of activities under the mantle of CBD. As I have explained in these remarks, there is no valid scientific basis to assume that 'biosafety' principles concerning GE organisms would have any effect whatever on the survival of biodiversity, which is so threatened throughout the world. In that sense, it seems to me to be a good thing that the CBD is now moving on to issues connected with the purpose for which it was formed, namely, the preservation of biodiversity.

Conclusions

There appear to be few situations in which limiting the planting of GE crops with the genes currently available would pose particular threats to biodiversity or to the environment generally. Indeed, the environmental damage caused by traditional farming systems, involving the application of large amounts of chemicals to the crops, would normally be much greater. It is proper to consider additional genes proposed for inclusion in commercial crops individually in terms of their effects, however. In that sense, the close consideration given to the new transgenic crops should also be applied to the extent considered desirable to other new strains of crops regardless of the ways in which they were produced.

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