Transgenic Crops: Implications for Biodiversity and Sustainable Agriculture

Maria Alice Garcia
Instituto de Biologia, Universidade Estadual de Campinas
Miguel A. Altieri
University of California, Berkeley

The potential for genetically modified (GM) crops to threaten biodiversity conservation and sustainable agriculture is substantial. Megadiverse countries and centers of origin and/or diversity of crop species are particularly vulnerable regions. The future of sustainable agriculture may be irreversibly jeopardized by contamination of in situ preserved genetic resources threatening a strategic resource for the world's food security. Because GM crops are truly biological novelties, their release into the environment poses concerns about the unpredictable ecological and evolutionary responses that GM species themselves and the interacting biota may express in the medium and long term. One of the consequences of these processes may be a generalized contamination of natural flora by GM traits and a degradation and erosion of the commonly owned genetic resources available today for agricultural development. GM plants carrying pharmaceutical and industrial traits will pose even more dangerous risks if released in the environment.

Keywords: *sustainable agriculture; transgenic crops; biodiversity; agroecology; organic farming*

INTRODUCTION

Genetically modified (GM) crops are becoming an increasingly common feature of agricultural landscapes. The total world's area planted to transgenic crops has increased dramatically, from 3 million hectares in 1996 to nearly 67.5 million hectares in 2003 (James, 2003). In the past 3 years however, the speed at which transgenic crops have displaced conventional crops has declined. The increase in area between 2001 and 2003 was 12%, equivalent to 6.1 million hectares. Globally, the main GM crop species planted in 2003 were soybeans, cotton, canola, and corn, respectively, 55%, 21%, 16%, and 11% of the global production. In the United States, Argentina, and Canada, more than half of the area planted to such major crops is occupied by transgenic varieties. Today, GM soybean covers about 3 million hectares only in Brazil, and about 20 countries have been reported as commercializing and planting transgenic varieties. Herbicide-tolerant (HT) crops and those expressing insecticidal toxins from the bacterium Bacillus thuringiensis (Bt) have been consistently the dominant traits in GM crops, although a range of other quality traits has been the subject of much research, and these are likely to be used commercially in the near future (Hilbeck, 2001). Among the new generation of GM crops to be approved for liberation are crop varieties modified to produce vitamins, vaccines, enzymes, and other industrial products, all of which may have unknown impacts on the environment and on the human food chain.

Promoters of GM crops promise high yields and solutions to the environmental problems caused by the intensive use of pesticides and that therefore they will be useful in fostering sustainable agriculture. But, why hasn't sustainable agriculture embraced GM crops? Longtime promoters of sustainable agriculture question the feasibility of these promises and point out the many threats GM crops pose to biodiversity and to the future of sustainable agriculture. Also, despite the ex-

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pectations that transgenic crops would protect the environment and benefit world agriculture, instead their release has prompted legal, political, and socioeconomic conflicts and many environmental concerns.

Transnational corporations, the main proponents of biotechnology, argue that carefully planned introduction of Bt and HT GM crops should reduce crop losses due to weeds, insect pests, and pathogens and reduce costs of production. They hold that the use of such crops will have added beneficial effects on the environment by significantly reducing the use of agrochemicals (Krimsky & Wrubel, 1996). It has been suggested that "if adequately tested," GM crops may promote a sustainable environment (Braun & Ammann, 2003). This view however is not universally shared among scientists, and some of them have become intensely involved in investigating the possible adverse effects of GM crops. Herren (2003) and Krebs, Wilson, Bradbury, and Siriwardena (1999) questioned whether we have learned sufficiently from the past, particularly from the naive optimism with which pesticides were initially embraced in the mid 20th century. Tappeser (2003) presented statistics showing the very small fraction, 3% or less, of biotechnology budgets spent on biosafety or biodiversity studies. A more careful analysis of data on GMO biosafety, such as that conducted by Marvier (2001), showed that even basic statistical tests and experimental designs, such as a reasonable number of repetitions, are not taken into account by corporations when conducting voluntary tests for environmental risk assessment. Wolfenbarger and Phifer (2000) also concluded that key experiments on environmental risks and benefits of GM crops are lacking. It is such weakness of regulatory and biosafety measures in the United States and in most countries that has favored the spread of transgenic crops all over the world. In January 2004 however, the National Research Council of the United States released a report calling for measures to prevent genetically engineered organisms from escaping into ecosystems or from spreading engineered traits to other species, recognizing the potential risks that GM crops may pose to people and to the environment. Such a call is a bit too late given the extent to which such crops have already spread worldwide.

Evaluating impacts and benefits of GM crops for biodiversity and sustainable agriculture is however a complex task that goes far beyond an overview of data and statistical analysis of papers showing trends or bias for or against GM. The main objective of this article is to use information available to examine the impacts that GM technology poses to biodiversity and farming in the context of an ecologically sound, socially just, economically viable, and environmentally friendly agriculture in the future.

POTENTIAL BENEFITS AND IMPACTS OF GM CROPS

Since the turn of the millennium there have been many studies on possible risks and benefits of GM crops, but long-term research experiments, crucial for evaluating ecological and health implications of GM crops, are sorely missing. The most extensive experiment covers only 3 years, reporting findings from farm-scale evaluations of the effects of herbicide-tolerant GM crops on various aspects of biodiversity (see Firbank, 2003). Most of the studies have explored different aspects of GM crops, such as environmental impacts (Dale, 2002; Fontes, Pires, Suji, & Panizzi, 2002; Hails, 2003; Jank & Gaugitsch, 2001), effects on ecosystem services (Lovei, 2001), farm biodiversity (Firbank, 2003; Firbank & Forcella, 2000; Watkinson, Freckleton, Robinson, & Sutherland, 2000), invertebrate fauna (Brooks et al., 2003; Haughton et al., 2003; Hawes et al., 2003; Roy et al., 2003), development of Bt resistance insect strains (Alyokhin & Ferro, 1999; Cerda & Wright, 2002), effects on weed abundance and diversity (Heard et al., 2003a, 2003b), changes in plant community structure resulting from gene flow (Gildings, 2000; Pascher & Gollmann, 1999), and ethical considerations (Dale, 2002; Garcia, 2001; J. Robinson, 1999). An extensive literature has developed also on the risks, utility, and challenges of Bt crops (e.g., Cannon, 2000; Edge, Benedict, Carroll, & Reding, 2001; Shelton, Zhao, & Roush, 2002).

Experience so far accumulated over the past years during which GM crops have been grown widely suggests several threats to the environment and to agricultural sustainability, but some authors also indicate possible advantages, particularly on intensive pesticide–dependent conventional crops. This view however is actively contested, and as explored in the following sections, there are many valid grounds to discount such claims. Because most of the GM crops so far commercialized carry traits either for insect or herbicide tolerance, we will focus on data from these most widespread GM crops (see Table 1).

Table 1. Summary of Possible Benefits and Impacts of Insect-Resistant and Herbicide-Tolerant Genetically Modified Crops

Potential Benefits	Potential Impacts
Reduced pesticide use	Enhancement of "clean-crop" and monoculture paradigm
Scope for threshold-driven herbicide use	Reduction of agroecosystem biodiversity
Simplification of farming practices	Increasing vulnerability of crops to environmental changes, new pests, and diseases
More efficient short-term production	Disruption of natural and biological control resources Promotion of secondary pests Impact on nontarget arthropods, soil biota, and biogeochemical cycles Selection of herbicide- and/or insect-resistant aggressive weeds Contamination and erosion of genetic resources for agriculture Contamination of natural flora and fauna (genetic pollution) Reduction of productivity due to yield drag effect on genetically modified crops Taking over of natural area by agriculture reducing biodiversity

POTENTIAL BENEFITS

Reduction of Pesticide Use

There are no studies that clearly support long-term reduction of pesticide use in GM crops. This is because studies tracking the use of all pesticides and herbicides (not only the ones that target the same pests that GM crops do) are lacking. For example, herbicide-resistant crops may reduce the use of Roundup but increase the need to use insecticides as insect pests may increase due to the reduction of certain weeds that provide nectar and pollen to natural enemies of those pests. Considering total pesticide use would allow reliable comparisons of total pesticide input per area, toxicity, and total area sprayed under GM and non–GM treatments in a large number of individual farms (Marvier, 2002). Based on more recent data (Champion et al., 2003), it seems that for herbicides, short-term reduction of inputs may occur for some crops but not for others, and reduction in herbicide use may be temporary, reverting after the 3rd year due to resistance development in certain weeds or due to weed species shifts. It is important to take all this into consideration when analyzing reports such as Phipps and Park (2002), which estimated GM soybean, corn, canola, and cotton to reduce pesticide used by 22.3 million kg of formulated product. In the case of Bt crops, in most of the corn-growing areas of the Midwestern United States, during the past 5 years, the percentage of field corn treated with insecticides has remained at approximately 30% despite a significant increase in the hectares of Bt corn planted (Obrycki, Losey, Taylor, & Jesse, 2001).

In the farm-scale evaluations of HT crops in the United Kingdom, auditing of herbicide use in GM sugar beet, maize, and oilseed rape and conventional non–GM crops showed that GM sugar beet generally received fewer herbicide sprays and less active ingredient per area than did the comparable conventional crops; however, for GM oilseed rape and forage maize, herbicide input was comparable to the national average (Champion et al., 2003). Therefore, the apparent benefits due to herbicide reduction are so far a matter of speculation.

If transgenic crop deployment proves to reduce pesticide use in the future, this would likely have a beneficial effect on the environment and biodiversity. In particular, reductions in pesticide use would reduce the pesticide-induced mortality of natural enemies—a critical aspect of conservation biological control (Barbosa, 1998; Gurr & Wratten, 2000; Gurr, Wratten, & Luna, 2003) with consequent benefits to pest management.

When compared with organically designed farms however, GM crops, either HT or Bt, appear increasingly pesticide dependent, whereas organic farms, following a completely different paradigm, do not rely at all on pesticides and thus constitute a more sustainable option.

Easier Management of Pests, Weeds, and Natural Enemies

Theoretically, pests and weeds could be managed more easily within GM crops than in conventional crops. Some argue that HT crops may offer options to bring more diversity to conventional agriculture. For example, by using herbicide-tolerant crops, farmers may create precise patterns of weed strips connecting field margins with field interiors and features such as beetle banks (Thomas, Wratten, & Sotherton, 1991). They may also favor beneficial arthropods by creating

Table 2. Trends of the Effects of Herbicide-Tolerant (GMHT) Crop Management on Density of Arthropods of Different Functional Groups in the Agroecosystem

Functional Groups of Arthropods	GMHT Beet (66 fields)	GMHT Maize (59 fields)	GMHT Oilseed Rape (67 fields)
Herbivores	Reduction	Similar	Similar
Predators	Similar	Similar	Reduction
Parasitoids	Reduction	Similar	Reduction
Detritivorous	Similar/increase	Increase	Similar/increase
Polinators	Reduction	Similar	Reduction

Source: Heard et al. (2003a, 2003b), Hawes et al. (2003), Brooks et al. (2003).
Note: Synthesis of data from 3 years farm-scale experiments in United Kingdom.

Table 3. Trends for Weed Communities in Areas Sown With Herbicide Tolerant (GMHT) Crops in Relation to Areas Sown With Conventional Crops

Parameters of Weed Community	GMHT Beet (66 fields)	GMHT Maize (59 fields)	GMHT Oilseed Rape (67 fields)
Density	Increase before spray Reduction after spray (reduction after treatment)	Increase before spray Increase after spray (higher (density all over de cycle)	Increase before spray Reduction after spray (reduction after treatment)
Final weed biomass	Reduction (one third to one sixth of conventional treatment)	Increase (82% higher than conventional treatment)	Reduction (one third to one sixth of conventional treatment)
Weed seed rain	Reduction	Increase (87% higher than conventional treatment)	Reduction
Weed diversity	Similar	Similar	Similar

Source: Heard et al. (2003a, 2003b), Hawes et al. (2003), Brooks et al. (2003).
Note: Synthesis of data from 3 years farm-scale experiments in United Kingdom.

islands or corridors of habitat diversity with flowering weeds. A network of habitat corridors would allow ease of movement by natural enemies from nearby habitats to disperse readily within crops, enhancing the speed with which a numerical aggregative response to pest foci may take place. The tendency in herbicide-tolerant GM crop farms however is for increasing biological homogeneity and easy overall herbicide spraying, fostering simplification of farming practices and enhancing economies of scale, in opposition to more sustainable practices such as selectively spraying to create precise patterns of habitats and species diversity. Given the intensification associated with GM crops, farming practices adopted in GM farms are not bringing the environmental benefits advertised by its promoters.

A synopsis of data produced by a UK experiment conducted by Hawes et al. (2003), Brooks et al. (2003), and Heard et al. (2003a, 2003b) indicates that weeds and arthropods may respond differently to each GM crop species. Generally, arthropod higher taxa were insensitive to differences between herbicide-tolerant GM crops and conventional weed management in non–GM crops; however, the densities of herbivores, predators, parasitoids, and pollinators changed in the same direction as the changes in weed biomass in each crop species (Tables 2 and 3). For butterflies in beet and canola and for *Heteroptera* and bees in beet, HT crops had lower populations inside the field and also on the vegetation of field margins (Haughton et al., 2003). Effects on soil invertebrates such as spiders and carabid beetles were approximately evenly balanced between increases and decreases in the GM crops compared with conventional crops (Roy et al., 2003). Generally, densities were increased in HT corn although decreased in HT canola and beet. Collembolan densities were significantly higher in HT crops, a trend that was considered to apply generally across cropping systems (Brooks et al., 2003). The importance of *Collembola* and other detritivores in pest management is that many are important components of the diets of generalist predators, so their presence could theoretically help maintain within-field communities of natural enemies, even during periods of prey scarcity. But data for predators do not confirm this expectation (Table 2).

Given the UK data, the situation is not clear-cut regarding the effects of HT crops on either the weed or arthropod community.

As stated by Heard et al. (2003a, 2003b), farmers may benefit from easier weed management if they learn to tolerate higher weed densities early in the season and to adopt threshold parameters for spraying. However, adoption of threshold parameters demands careful monitoring of the farm and extra work. Instead, the advantage farmers are taking from GM crops is mainly the simplification of farming practices. They may spray anywhere, anytime, without harming the crop but not realizing that there may be unwanted effects. Such a nondiscriminatory approach does not allow for a more sophisticated management of flora biodiversity and habitats needed for the enhancement of natural enemies. Also, without legislation, it remains to be seen whether profit-driven agriculturalists would adopt such practices.

Simplification of Farming Practices and Increasing of Efficiency

Additional benefits claimed for GM crops include higher efficiency and increased yields and profits. These possible economic benefits may only be associated with the simplification of farming practices and reduced costs of applying pesticides. So far, there are no data that support higher yields for GM crops. In fact, in many cases what has been observed is a reduction in GM crop yields (*yield-drag*) compared to those obtained by non–GM varieties (Benbrook, 1999; Elmore et al., 2001). Simplification of farming practices, particularly for herbicide-tolerant crops, where farmers may spray all over the field at any time instead of worrying about being space selective and time precise can give a false impression of productivity. GM crops tend to reduce labor demand and increase the short-term efficiency of farming practices but in detriment of agroecosystem biodiversity, natural and biological control, and even yields. Such combination of effects has not been considered when analyzing GM impacts and benefits.

POTENTIAL IMPACTS

GM crop species currently being introduced carry particular traits that make them biological novelties to the ecosystem. The potential impacts of these crops, summarized in Table 1, are mainly associated with ecological processes operating and molding agroecosystems. GM crop species will interact with the other component species of the agroecosystem and surrounding environments, potentially affecting their fitness, population dynamics, ecological roles, and interactions, promoting local extinctions, population explosions, and changes in community structure and function inside and outside agroecosystems. Events that directly or indirectly may result on impacts have been explored by many authors (see e.g., Altieri, 2000; Garcia, 2001; Gildings, 2000; Kendall et al., 1997; Rissler & Mellon, 1996; Snow & Moran, 1997) and may include the following:

a. the spread of transgenes to wild or weedy relatives;
b. reduction or increase of the fitness of nontarget organisms (especially weeds or local varieties) through the acquisition of transgenic traits via hybridization;
c. the evolution of resistance of insect pests, such as *Lepidoptera* and *Coleoptera*, to Bt toxins;
d. accumulation of the Bt toxins, which remain active in the soil after the crop is plowed under and bind tightly to clays and humic acids;
e. disruption of natural control of insect pests through intertrophic-level effects of the Bt toxin on natural enemies;
f. unanticipated effects on nontarget herbivorous insects;
g. vector-mediated horizontal gene transfer (i.e., to unrelated taxa) and recombination to create new pathogenic organisms;
h. escalation of herbicide use in HT crops with consequent environmental impacts including reduced weed populations and diversity;
i. reduced weed populations leading to declines in bird populations that feed on or shelter in weeds or feed on the arthropods supported by weeds;
j. reduced weed diversity leading to higher pest damage because of resource concentration (Root, 1973) effects or impoverished natural enemy communities;
k. selection of herbicide-resistant and more noxious weeds.

GM technology may also reinforce genetic homogeneity and promote large-scale monocultures, increasing vulnerability of crops to climatic change, pests, and diseases. The aim of this section is not to open a debate concerning the value and limitations of each potential impact or risks already listed but to combine them into related topics aiming to illustrate their implications for biodiversity and sustainable agriculture.

Promotion of "Clean Farming" and the Monoculture Paradigm While Reducing Biodiversity

GM crops available so far encourage agricultural intensification, and as long as the use of these crops follows closely the high-input, pesticide paradigm, such biotechnological products will reinforce the "pesticide treadmill" usually associated with genetic uniformity and reduction of biodiversity in agroecosystems. To the extent that transgenic crops further entrench the current clean crop monoculture system, they discourage farmers from using other ecologically based pest management methods (Altieri, 1996), including simple ecological approaches like biodiversity islands, field margins, and corridors. Monocultures also limit the extent to which farm lands—which cover large areas of the world (e.g., 70% on the United Kingdom; Hails, 2003)—can contribute to conservation of wildlife.

There is wide acceptance of the importance of field margins as reservoirs of natural enemies of crop pests as these habitats provide sources of alternative prey/hosts or pollen and nectar and provide shelter. Parasitism of the armyworm, *Pseudaletia unipunctata*, was significantly higher in maize fields embedded in a complex landscape than in maize fields surrounded by simpler habitats. In a 2-year study, researchers found higher parasitism of *Ostrinia nubilalis* larvae by the parasitoid *Eriborus terebrans* in edges of maize fields adjacent to wooded areas than in field interiors (Landis, Wratten, & Gurr, 2000). Similarly in Germany, parasitism of rape pollen beetle was about 50% at the edge of the fields, whereas at the center of the fields, parasitism dropped significantly to 20% (Thies & Tscharntke, 1999).

Direct benefits of biodiversity in agriculture lie in the range of ecosystem services provided by the different biodiversity components. These include nutrient cycling, pest regulation, pollination, and others (Gurr et al., 2003). In relation to pest management, the widespread use of crop monocultures and attendant genetic homogeneity are often associated with elevated pest densities. Because the use of GM crops reinforces this simplification of farming systems, a range of negative consequences could accrue affecting ecosystem services and agroecosystem function. To the contrary, organic agriculture benefits from decades of using ecological principles based on diversification, low external inputs, resources conservation, and biological services. In developing countries, traditional farmers have for centuries successfully used ecological principles to design locally adapted and sustainable agroecosystems. These systems comprise alternatives to the conventional farms but may be negatively affected by the widespread use of GM crops.

Increasing Vulnerability

There is no doubt that agriculture constitutes a major cause of the loss of biodiversity (Conner, Glare, & Nap, 2003). Agriculture typically represents an extreme form of simplification of terrestrial biodiversity because monocultures, in addition to being genetically uniform and species-poor systems, advance at the expense of noncrop and natural vegetation, key landscape components that provide important ecosystem services.

Since the onset of agricultural modernization, farmers and researchers have been faced with an ecological dilemma arising from the homogenization of agricultural systems: an increased vulnerability of crops to unpredictable arthropod pests and diseases, which can be devastating when infesting genetically uniform, large-scale monocultures (R. A. Robinson, 1996). Examples of disease epidemics associated with homogeneous crops abound in the literature, including the $1 billion disease-induced loss of maize in the United States in 1970 and the 18 million citrus trees destroyed by pathogens in Florida in 1984 (Thrupp, 1998).

Increasingly, evidence suggests that changes in landscape diversity due to monocultures have led to more insect outbreaks due to the removal of natural vegetation and decreasing habitat diversity (Altieri, 1994; Garcia, 2001). One of the main characteristics of the transgenic agricultural landscape is the large size and homogeneity of crop monocultures that fragment the natural landscape. This can directly affect abundance and diversity of herbivores and natural enemies as the larger the area under monoculture, the lower the viability of a given population of beneficial fauna. At the field level, decreased plant diversity in agroecosystems allows greater chance for invasive species to colonize, subsequently leading to enhanced herbivorous insect abundance. Many experiments have shown fairly consistent results: Specialized herbivore species usually exhibit higher abundance in monoculture than in diversified crop systems (Andow, 1991).

In Brazil, as well as in many other developing countries, because local seed companies have been bought by transnational biotechnology companies, all the investment for building capacity for self-reliance on crop seeds of varieties well adapted to different environments may be lost in the coming years. This is not just a political and economic issue but represents a serious ecological threat to sustainable agriculture in these countries. Considerable increase on crop vulnerability is expected as the extent that local adapted varieties will be displaced by more uniform GM varieties.

GM Yield Drag

The reduction of yields (yield drag) in GM crops compared to what farmers would obtain if they used the best adapted non–GM crop varieties may be compensated by economies of scale and incorporation of new land. This reinforces the biotech agriculture tendency to expand at the expense of natural vegetation and the associated destruction of biodiversity.

Monocultures of any type of crop, irrespective of whether GM or conventional, may constitute the most widespread impediment to sustainable pest management. Thus, the evidence that GM crops strongly encourage monoculture and increase vulnerability conflicts with sustainable agriculture. Similarly, GM technology associated with herbicide- and insect-resistant crops also conflicts with organic and other well-established and successful ecologically based options of farming. Particular threats are analyzed in the following sections.

Threats Associated With Herbicide-Resistant Crops

Development of weed resistance. A concern with transgenes from HT crops is that through gene flow they may confer significant biological advantages to other plants, transforming wild/weedy plants into new or worse weeds. Hybridization of HT crops with populations of free-living relatives would make these plants increasingly difficult to control, especially if they are already recognized as agricultural weeds and if they acquire resistance to widely used herbicides. The GM crop itself may also assume weed status, in crops that follow later in a rotational cropping system for example. In Canada, volunteer canola resistant to three herbicides (glyphosate, imidazolinone, and glufosinate) has been detected, a case of “stacked” or resistance to multiple herbicides (Hall, Topinka, Huffman, & Good, 2000). Reliance on HT crops also perpetuates the weed resistance problems and species shifts that are common to conventional herbicide-based approaches. Herbicide resistance becomes more of a problem as the number of herbicide modes of action to which weeds are exposed becomes fewer and fewer, a trend that HT crops may reinforce due to market forces. Given industry pressures to increase herbicide sales, areas treated with broad-spectrum herbicides could expand, exacerbating the resistance problem. In the United States, *Lolium* species, *Eleusine* species, and *Conyza canadensis* have already been reported as resistant to glyphosate (Heard et al., 2003a). Selection of herbicide-resistant species, besides reducing diversity, can induce a weed community more difficult to manage by chemical methods or by other practices usually used by organic farmers.

Impact on flora and fauna biodiversity. Some weeds are important components of agroecosystems because they positively affect the biology and dynamics of beneficial insects. Noncrop vegetation offers many important resources for natural enemies, such as alternative prey/hosts, pollen, or nectar as well as microhabitats that are not available in weed-free monocultures (Landis et al., 2000). Many insect pests are not continuously present in annual crops, and their predators and parasitoids must survive elsewhere during their absence. Weeds can provide such resources, thus aiding in the persistence of viable natural enemy populations. Crop fields with a dense weed cover and high diversity usually have more predacious arthropods than do weed-free fields (Garcia, 1991). The successful establishment of parasitoids usually depends on the presence of weeds that provide nectar for the adult female wasps. Relevant examples of cropping systems in which the presence of specific weeds has enhanced the biological control of particular pests were reviewed by Altieri and Nicholls (2004).

Accordingly, perhaps the greatest problem associated with the use of HT crops is the fact that associated broad-spectrum herbicides offer scope to completely remove weeds from fields, reducing plant diversity in agroecosystems. This contrasts with herbicidal weed management approaches in conventional crops where selective herbicide use may leave some weed taxa present. Many studies have produced evidence that the manipulation of a specific weed species or a particular weed control practice can affect the ecology of insect pests and associated natural enemies (Altieri & Letourneau, 1982).

Even though HT crop/herbicide package could potentially allow more rational weed management with potential benefits for arthropod pest management, the goal of achieving season-long total weed control in all crops reinforces the loss of diversity and biological services in conventional farms. By reviewing weed phenologies and population models, Freckleton et al (2004) showed that weed diversity is unlikely to increase in HT fields because spraying is generally delayed to the point that most weeds do not set seeds. These authors suggested that the positive effects on biodiversity observed in some trials are likely to be transient, and therefore, one cannot expect that beneficial arthropods and birds using resources from weeds will benefit from the use of herbicide-tolerant crops. Organic farmers on the other hand are used to a different concept and recognize the positive effects that weeds may have on natural enemies' ecology and on soil conservation. Traditional and organic farmers avoid crop loss due to weed competition and reduce labor demand by adopting a more precise timing and selective approach to weed management. Consequently, organic farmers guarantee a permanent high plant biodiversity inside and along the field margins, which usually enhances natural pest control.

British farm-scale evaluations (Haughton et al., 2003; Roy et al., 2003) showed that reduction of weed biomass, flowering, and seeding of plants under HT crop management within and in margins of beet and spring oilseed rape involved changes in resource availability with knock-on effects on higher trophic levels reducing abundance of relatively sedentary and host specific herbivores including *Heteroptera* and butterflies and bees. Counts of predacious carabid beetles that feed on weed seeds were also smaller in HT crop fields (see also Table 3). In accord to Heard et al. (2003b) data, over time, weed species that are less susceptible to glyphosate and/or glufosinate ammonium, such as *Viola arvensis*, *Lamium* species, *Chenopodium album*, and *Veronica persica*, will probably be favored in GMHT crops. It is possible that selection will lead to dominance of the weed flora by a reduced number of more herbicide-tolerant species. This impoverished weed community may reduce diversity of arthropod community and biological services they provide to agroecosystems. Researchers also recorded lower biomass for many species of weeds among the two HT crops, which led them to conclude that these differences compounded over time would result in large decreases in population densities of arable weeds. The abundance of invertebrates, which in turn serve as food for mammals, birds, and other invertebrates, are important for controlling pests or recycling nutrients within the soil, was also found to be generally lower in HT beet and canola. Specifically, a reduction in bees was associated with fewer flowering weeds in the GM beet, which also has clear implications for natural enemies of pests, such as aphidophagous syrphids and parasitoids that—like bees—require weed flowers for nectar and pollen.

It is noteworthy that although the British farm-scale evaluations were ambitious in scale and rigorous in design, like all scientific investigations, they were naturally contained, and this limits the extent to which findings can be generalized (Firbank, 2003). For example, organic systems where biodiversity levels may be considerably higher were not included in the comparisons. Furthermore, although densities of natural enemies were measured, process rates such as predation and parasitism of pests were not investigated. Particularly important to investigate are the consequences on neighboring flora and fauna of a significant higher level of pesticide drift reported by Roy et al. (2003) for all the GMHT crops analyzed in the UK experiment. This issue is of great health and environmental significance and constitutes a major source of direct conflict between GM and organic and traditional ways of farming.

Threats Associated With Bt Crops

Insect pest resistant to Bt and weeds resistant to insects. Based on the fact that more than 500 species of pests have already evolved resistance to conventional insecticides, pests can also evolve resistance to Bt toxins present in transgenic crops (e.g., Gould, 1998; Sayyed, et al, 2003). Because Bt is being successfully used for decades as a biological control agent and is particularly valuable to organic farmers that do not use pesticides, this resource may be quickly depleted by inappropriate use of Bt crops. Transgene for Bt toxin may also be transferred by hybridization to wild or weed relatives of GM crop species. These wild species may benefit by escaping damage by insect herbivory and may become serious weeds or may also outcompete and locally extinguish other species in natural environment.

There is a parallel between current Bt crops and primitive (i.e., circa 1950s-1970s) calendar spraying in which insecticides were applied regularly during the growth of a crop irrespective of pest presence or density. Despite all the pressures for U.S. farmers to use insect-resistant GM varieties, benefits from using transgenic corn are not assured because population densities of the key pest, European corn borer (ECB), are not predictable, and outbreaks of secondary pests have led farmers to spray extra insecticides (Levidow, 2003). The ECB does not attain equal pest proportions in all regions and seems to be a problem every 4 to 8 years. In years when the ECB is not a pest, it is not economical for farmers to use Bt corn.

Bt and other insect-resistant crops express toxins more or less uniformly over the plant and continuously over their lives, thus exposing continually the pest population to a selection pressure. In contrast, the use of Bt sprays are generally applied in response to monitoring of pest densities and may be alternated with other pest management strategies (e.g., other pesticides or inundative biological control products) to minimize the development of resistance in the pest.

The farmers that face the greatest risk from the development of insect resistance to Bt are neighboring organic farmers who grow crops without agrochemicals. Once resistance appears in insect populations, organic farmers will not be able to use Bt in its microbial insecticide form to control the lepidopteran pests that move in from adjacent neighboring transgenic fields. In addition, genetic pollution of organic crops resulting from gene flow (pollen) from transgenic crops can jeopardize the certification of organic crops, forcing organic farmers to lose premium markets.

Because of gene flow, Bt traits may be transferred to wild crop relatives by hybridization. If these plants benefit from reduced herbivory, they may increase their fitness and become serious problems inside and outside agroecosystems. Snow et al. (2003) demonstrated that wild sunflower that was hybridized with Bt sunflower produced significantly more viable seeds per plant than nontransgenic plants. The authors suggested that the increased fitness of hybrid plants is largely due to reduction on root and stem damage caused by lepidoptera larvae. This can trigger as high as 55% increase in seed production on wild transgenic plants. Strong suppression of herbivory was also reported for a weed species *Brassica rapa* with Cry1Ac transgene (Halfhill, Millwood, Rymer, & Stewart, 2002), indicating that clearly Bt transgenes may dramatically increase the fitness of wild and weed species by reducing herbivory. This suggests that selection favoring an increase of frequency of Bt transgene in wild species is potentially high, with unpredictable ecological and evolutionary consequences. The magnitude of such threat for biodiversity and sustainable agriculture cannot be estimated, but many authors have pointed out that the risk of genetic pollution is not only serious for crop genetic resources available for agriculture but also for wild species in nature. Recently, the National Resource Council of the United States (2004) called for measures to prevent genetically engineered organisms from escaping into ecosystems and from spreading GM traits in nature.

Bt crops and beneficial insects. Bt proteins are becoming ubiquitous, bioactive substances in agroecosystems present for many months. Most if not all nontarget herbivores colonizing Bt crops in the field, although not lethally affected, ingest plant tissues containing Bt protein that they can pass on to their natural enemies. Polyphagous natural enemies that move between crops are likely to encounter Bt containing nontarget herbivorous prey in more that one crop during the entire season. According to Groot and Dicke (2002), natural enemies may come in contact more often with Bt toxins via nontarget herbivores because the toxins do not bind to receptors on the mid-gut membrane in the nontarget herbivores. This is a major ecological concern given studies that documented that the Bt toxin Cry1Ab adversely affected the predacious lacewing *Chrysoperla carnea* reared on Bt corn–fed prey larvae (Hilbeck, 2001; Hilbeck, Baumgartner, Fried, & Bigler, 1998; Hilbeck, Moar, Pusztai-Carey, Filippini, & Bigler, 1998).

Sublethal effects show scope for the fitness of natural enemies to be indirectly affected by Bt toxins exposed to GM crops via feeding on suboptimal food or because of host death and scarcity (Groot & Dicke, 2002). Moreover, the toxins produced by Bt plants may be passed on to predators and parasites in plant material (pollen and at times such as in the case of *Geocoris* species, via leaf tissue). Nobody has analyzed the consequences of such transfers on the myriad of natural enemies that depend on pollen for reproduction and longevity. Furthermore, although nectar does not contain insecticidal gene products, parasitoids inadvertently ingest pollen when taking nectar, and this exposes them directly to toxins within the pollen. Finally, because of the development of a new generation of Bt crops with much higher expression levels, the effects on natural enemies reported so far (Table 4 and Appendix for details) are likely to be an underestimate of future impacts.

Although not conclusive, the data in Table 4 indicate that neutral and detrimental effects of Bt crops are more common than positive effects. Also, predator species seem to be less affected than parasitoid species. Among the natural enemies that live exclusively on insects the Bt crops are designed to kill (chiefly *Lepidoptera*), egg and larval parasitoids would be most affected because they are totally dependent on live hosts for development and survival, whereas some predators could theoretically thrive on dead or dying prey (Schuler, Poppy, Potting, Denholm, & Kerry, 1999). Although the Bt toxin expression is the insect resistance trait most widely used in GM crops, expression of the snowdrop lectin GNA has also been engineered into potato. For this toxin, Birch et al. (1999) showed a deleterious effect on fecundity, egg viability, and longevity of two spot ladybird (*Adalia bipunctata*). Subsequent studies suggested that these effects on the predator are the result of reduced weight of individual aphids when reared on GNA-expressing plants rather than a direct effect of the toxin on the third trophic level (Conner et al., 2003).

The fact that natural enemies can be affected directly through intertrophic level effects of the toxin present in Bt crops (Table 6) raises concerns about the potential disruption of natural pest control as polyphagous predators that move within and between crop cultivars will encounter Bt-containing, nontarget prey throughout the crop season. These findings are problematic for small farmers in developing countries and also diversified organic farmers who rely for insect pest control on the rich complex of predators and parasites associated with their mixed cropping systems. Disrupted biocontrol mechanisms will likely result in increased crop losses due to pests or to increased use of pesticides by farmers, with consequent health and environmental hazards.

When analyzing the magnitude of any negative effects of insect-resistant GM crops on natural enemies, it is important to consider that in the majority of cases, the alternative to their use is an insecticide spray program whose impacts on beneficial arthropods can be substantial. This is valid only if it is possible to show reductions of pesticide use in GM monocultures. On the other hand, organic and traditional systems already rely heavily on natural enemies for pest control. Even though the total area of organic farmland, where farmers apply habitat manipulation approaches, is comparatively small, these agroecosystems are a particularly appropriate reference point to evaluate GM effects as they usually express maximum levels of biodiversity.

Effects on the soil ecosystem. The possibilities for soil biota to be exposed to transgenic products are high. The little research conducted in this area has already demonstrated persistence of insecticide products (Bt and proteinase inhibitors) in soil after exposure to decomposing microbes (Donegan et al., 1997). The insecticidal toxin produced by *Bacillus thuringiensis subsp. Kurstaki* remains active in the soil, where it binds rapidly and tightly to clays and humic acids. The bound toxin retains its insecticidal properties and is protected against microbial degradation by being bound to soil particles, persisting in various soils for 234 days (Palm, Schaller, Donegan, & Seidler, 1996). Palm et al. (1996) found that 25% to 30% of the Cry1A proteins produced by Bt cotton leaves remained bound in the soil even after 140 days. In another investigation, researchers confirmed the presence of the toxin in exudates from Bt corn and verified that it was active in an insecticidal bioassay using larvae of the tobacco hornworm (Saxena, Flores, & Stotzky, 1999). In a recent study, after 200 days of exposure, adult earthworms, *Lumbricus terrestris*, experienced a significant weight loss when fed Bt corn litter compared with earthworms fed on non–Bt corn litter (Zwahlen, et al 2003). Potentially these earthworms may serve as intermediaries through which Bt toxins may be passed on to organisms feeding on these earthworms. Given the persistence and the possible presence of exudates, there is potential for prolonged exposure of the microbial and invertebrate community to such toxins, and therefore studies should evaluate the effects of transgenic plants on both microbial and invertebrate communities and the ecological processes they mediate.

If transgenic crops substantially alter soil biota and affect processes such as soil organic matter decomposition and mineralization, this would be of serious concern to organic farmers and most poor farmers in the developing world who cannot purchase or do not want

Table 4. Summary of Number of Species of Natural Enemies to Which There Are Reports on Effects Due to Crops Genetically Modified for Insect Tolerance

Taxa of Natural Enemy	Negatively Affected	Positively Affected	Not Affected
Total coleoptera (5 species + general fauna)	2 species + general fauna		4 species + general fauna
Total diptera (3 species)	2 species		1 species
Total dermaptera (1 species)		1 species	1 species
Total hemiptera (7 species)		1 species	6 species + general hemiptera fauna
Total hymenoptera (9 species)	4 species	2 species	8 species
Total neuroptera (2 species)	2 species		1 species
Total predators (17 species)	5 species	2 species	15 species
Total parasitoids (10 species)	5 species	2 species	7 species

Motified from: Fontes, Pires, Sujii, and Panizzi (2002).

to use chemical fertilizers and that rely instead on local residues, organic matter, and especially soil organisms for soil fertility (i.e., key invertebrate, fungal, or bacterial species) that can be affected by the soil-bound toxin. Soil fertility could be dramatically reduced if crop leachates inhibit the activity of the soil biota and slow down natural rates of decomposition and nutrient release. Due to accumulation of toxins over time during degradation of plant biomass, the doses of Bt toxin to which these soil organisms are exposed may increase with time, so impacts on soil biology could be worse and longer term. Again, very little information is available on the potential effects of such toxins on soil-inhabiting predacious fauna (beetles, spiders, etc.) and the pest consequences associated with potential reductions of beneficial ground predators.

Studies by Settle et al. (1996) in tropical Asian irrigated rice agroecosystems showed that by increasing organic matter in test plots, researchers could boost populations of detritivores and plankton feeders and in turn significantly boost the abundance of generalist predators. Surprisingly, organic matter management proved to be a key mechanism in the support of high levels of natural biological control. Bt toxins can potentially disrupt such mechanisms, thus indirectly promoting pest outbreaks.

Nematodes are another important component of soil ecosystems, and the effects of Bt toxins from GM plants on these have been little studied. Manachini and Lozzia (2002) showed that there was no significant effect of Bt corn cultivation on nematode fauna, although a change in trophic groups was noted for one region, and a need for longer term studies was pointed out.

HT crops can affect soil biota indirectly through effects of glyphosate, the application of which may be encouraged by some HT crops. This herbicide appears to act as an antibiotic in the soil, inhibiting mycorrizae, antagonists, and nitrogen-fixing bacteria. Root development, nodulation, and nitrogen fixation is impaired in some HT soybean varieties that exhibit lower yields, and these effects are worse under drought stress or infertile soils (Benbrook, 2001). Elimination of antagonists could render GM soybean more susceptible to soil-borne pathogens.

GENERAL ISSUES AND CONCLUSIONS

Whereas the potential for GM crops to benefit biodiversity conservation and sustainable agriculture is negligible or at least questionable, the potential for impacts or threats of GM technology given the evidence so far appears substantial, particularly because GM crops are truly biological novelties that would not exist via natural processes. The release of these new biological phenotypes into the environment has led to serious concerns about the unpredictable ecological and evolutionary responses GM species and the interacting biota may express in the medium and long terms. One of the consequences of these processes may be a generalized contamination of natural flora by GM traits and a degradation and erosion of the commonly owned genetic resources today available for agricultural development. Ecological concerns therefore are not limited to pest resistance and creation of new weeds or virus strains (Kendall et al., 1997). As argued herein, transgenic crops produce toxins that can move through the food chain and also end up in the soil where they bind to colloids and retain their toxicity, affecting invertebrates and possibly nutrient cycling (Altieri, 2000). It is virtually impossible to quantify or predict the long-term impacts on agrobiodiversity and the processes they mediate resulting from widespread use of GM crops.

There is a clear need to further assess the severity, magnitude, and scope of risks associated with the use of transgenic crops. Much of the evaluation of risks must move beyond comparing GM fields and conventionally managed systems to include organic and other alternative cropping systems featuring crop diversity and low-input approaches. These systems express higher levels of biological diversity and thus allow scientists to capture the full range of impacts of GM crops on biodiversity and agroecosystem processes.

Moreover, the increased landscape homogenization that could result from GM crops will exacerbate the ecological problems already associated with monoculture agriculture (Altieri, 2000). Unquestioned expansion of this technology into developing countries may not be wise or desirable, particularly into tropical areas where centers of biodiversity could be threatened (Kathen, 1996). There is strength in the agricultural diversity of many of these countries, and it should not be jeopardized by extensive monoculture, especially when consequences of doing so result in serious social and environmental problems (Altieri, 1996).

The repeated use of transgenic crops in an area may result in cumulative effects such as those resulting from the build-up of toxins in soils. For this reason, risk assessment studies not only have to be of an ecological nature to capture effects on ecosystem processes but also of sufficient duration so that probable accumulative effects can be detected. Manachini and Lozzia (2002) stressed the need for longer term risk assessment. A decade of carefully monitored field ecology is necessary to assess the full potential risks resulting from GM crops to the environment. Eventual decreases in pesticide use and simplification of farming practices are not acceptable as proxies for environmental benefits. The application of multiple diagnostic methods to assess multitrophic effects and impacts on ecosystem structure and function will provide the most sensitive and comprehensive assessment of the potential impact of GM crops on biodiversity and on the development of sustainable agriculture.

Until these studies are completed, a moratorium on transgenic crops based on the precautionary principle should be imposed as a biosecurity measure everywhere. Megadiverse countries and centers of origin and/or diversity of crop species are particularly vulnerable regions. The future of sustainable agriculture may be irreversibly jeopardized by contamination of in situ preserved genetic resources. Fontes (2003) pointed out that we should look closely to any threat to that strategic resource for the world's food security. Precautionary principle advises that instead of using the criterion the "absence of evidence" of serious environmental damage, the proper decision criterion should be the "evidence of absence," in other words avoiding Type II statistical error—the error of assuming that no significant environmental risk is present when in fact risk exists. This signals a need for clear laws and regulation for GM liberation into the environment.

Although biotechnology may be a powerful and intellectually stimulating tool, GM crops are developed largely for profit motives and as argued in this article, carry significant yet hard to quantify risks. GM plants carrying pharmaceutical and industrial traits, the next generation of transgenic crops, pose even more dangerous risks if released in the environment, especially as containment of transgenes is not assured. Equivalent levels of research and development investment have not been made in ecological approaches, at least partly because the solutions generated by habitat manipulation approaches are management based rather than product based. This presents few opportunities for patenting and revenue generation from intellectual property, so private investment on agroecology is unlikely to become significant. This suggests a need for government and for university researchers to invest public resources in such research because development of sustainable agriculture compatible with biodiversity conservation will not be achieved relying on the dominant genetic-engineering-based options.

APPENDIX
Registered Effects on Natural Enemies Due to Crops Genetically Modified for Insect Tolerance

Taxa of Natural Enemy	Parameter Negatively Affected	Parameter Positively Affected	Parameter Not Affected
Coleoptera			
Carabidae			
Lebia grandis	Density (Riddick, et al 1998)		Prey consumption (Riddick & Barbosa, 2000)
Carabidae fauna	Density (Brazil - CTNBio 1999a)		Density (Brazil - CTNBio 1999b)
Coccinellidae			
Adalia bipunctata	Eclosion rate, female longevity, fecundity (Birch et al., 1999)		
Coccinella septempunctata			Density (Bouguet et al., 2002)
Coleomegilla maculata			Density (Orr & Landis, 1997), development, survivorship (Lundgreen & Weedenman 2002; Pilcher, et al 1997)
Hipodamia convergens			Density (Pilcher et al., 1997), survivorship (Sims, 1995, 1997), fitness (Keller & Langenbruch, 1993)
Coccinellidae fauna			Density (Brazil - CTNBio 1999b)
Total Coleoptera 5 species + general fauna	2 species + general fauna		4 species + general fauna
Diptera			
Tachinidae			
Lydella thompsoni	Parasitism rate (Bouguet et al., 2002)		
Pseudoperichaeta nigrolineata	Parasitism rate (Bouguet et al., 2002)		
Syrphidae			
Syrphus corollae			Density (Bouguet et al., 2002)
Total Diptera 3 species	2 species		1 species
Dermaptera			
Forficulidae			
Doru luteipes		Density (Brazil-CTNBio 1999 a, b)	Density (Brazil-CTNBio 1999 a, b)
Total Dermaptera 1 species		1 species	1 species

(continued)

Appendix (continued)

Taxa of Natural Enemy	Parameter Negatively Affected	Parameter Positively Affected	Parameter Not Affected
Hemiptera			
Anthocoridae			
Orius insidiosus			Density (Bouguet et al., 2002; Orr & Landis, 1997; Pilcher et al., 1997), survivorship, development (Pilcher et al., 1997)
Orius majusculus			Development, survivorship (Zwahlen, et al, 2000)
Orius tristicolor			Longevity (Armer, et al, 2000)
Berytidae			
Jalysus wickhami		Predation rate (Johnson & Gould, 1992)	
Lygaeidae			
Geocoris species			Longevity (Armer et al., 2000)
Miridae			
Lygus hesperus			Longevity (Armer et al., 2000)
Nabidae			
Nabis species			Longevity (Armer et al., 2000)
Predator hemiptera fauna			Density (Brazil-CTNBio 1999b)
Total Hemiptera 7 species		1 species	6 species + general hemiptera fauna
Hymenoptera			
Braconidae			
Cardiochiles nigriceps		Parasitism rate (Johnson & Gould, 1992)	Parasitism rate (Johnson, 1997)
Cotesia plutelae	Emergence rate, attraction to susceptible host (Schuler et al., 2001; Schuler, et al 1999; a, b		Emergence rate, attraction to resistant host (Schuler, et al., 1999a)

Appendix (continued)

Taxa of Natural Enemy	Parameter Negatively Affected	Parameter Positively Affected	Parameter Not Affected
Diaeretiella rapae			Parasitism rate (Schuler, et al., 1999b; 1999)
Macrocentrus cirgulum (formerly M. grandis)	Density (Pilcher, 1999)		Parasitism rate on non transgenic plants in transgenic plots(Orr & Landis, 1997; Pilcher, 1999)
Eulophidae			
Eulophus pennicornis	Parisitism rate (Bell et al. 2001)		Parasitism rate, development on host and artificial diet (Bell et al. 2001)
Ichneumonidae			
Campoletis sonorensis		Parisitism rate Johnsons & Gould 1992, Johnson 1997)	
Erioborus terabrans			Parisitism rate (Orr & Landis 1997)
Pteromalidae			
Niasonia vitripennis			Mortality host from diet (Sims 1995, 1997)
Sphecidae			
Stictia species	Density (Brazil CTNBio 1999a)		Density (Brazil CTNBio 1999a)
Total Hymenoptera 9 species	4 species	2 species	8 species
Neuroptera			
Chrysopidae			
Chrysoperla carnea	Survivorship, development, mortality host from plant and diet (Hilbeck 1998a, b, 1999		Density (Bouget et al. 2002, Pilchen 1999, development (Lozia et al., Pitchet et al. 1997) survival (Pilchet 1999)
Hemerobidae			
Hemerobius species	Density (Brazil CTNBio 1999a)		
Total Neuroptera	2 species		1 species
Total predators	5 species	2 specie	15 species
Total parasitoids	5 species	2 speciess	7 species

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Maria Alice Garcia, biologist, PhD in ecology, professor of ecology and entomology at Universidade Estadual de Campinas, UNICAMP, São Paulo, Brasil.

Miguel Angel Altieri, agronomist, PhD in ecology, professor of agroecology at University of California, Berkeley.